# ULTRASONICS

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# ULTRASONICS

*By* BENSON CARLIN

*Formerly with Sperry Products*

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ULTRASONICS

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# PREFACE

There has been a tremendous growth in the science of ultrasonics within the past few years. It is very possible that in its width of application it will soon rival many older sciences. However, because of this very rapidity of growth, and because most of the earlier work was done in foreign countries, the published material now obtainable here is scattered and repetitious. Most of the available references are mere compilations of the work of the same four or five men, repeated and reedited. The author hopes that this book will correlate and add to the prior work. Naturally much of the material, especially the theoretical parts, is well known in the art, and it can have but little claim to originality, but almost all the practical experimentation was personally carried out by the author, both in repeating the investigations of prior workers and along original lines as they suggested themselves to him. It is, of course, very likely that other workers in the field have carried out similar investigations. Full credit has been given wherever the author was familiar with such work. It is hoped that further studies will be suggested by the information contained here.

The author has worked at the University of Michigan as a visiting engineer for a period during the development of the ultrasonic Reflectoscope and later as a senior research and product engineer for the Sperry Products Corporation. He wishes to extend his thanks to his many colleagues whose suggestions and advice have often been valuable.

It is possible that credit may not always be given where it is due, since much material became known to the author anonymously. Such slights are entirely unintentional and will be corrected gladly when called to his attention.

This work is not primarily a historical one, and no attempt has been made to include mention of all the workers in the field or to compile prior work. Rather, this discussion leans to the practical and engineering sides. Well-known theories and works are therefore presented as statement of fact, without derivations and histories of development.

Most work until very recently has been theoretical rather than in the direction of application. This work, however, is slanted in the latter manner and, it is hoped, will encourage further work in that direction.

The published articles and books on ultrasonics have been few. However, the applications are so numerous that they merit special attention. These now include among them the following:

1. The mixing of ordinarily immiscible liquids.
2. The dispersion of metals in liquids.
3. The breaking up of some polymers.
4. Coagulation of certain suspensions.
5. Production of heating effects.
6. Production of chemical reactions.
7. Precipitation of smoke.
8. Homogenization.
9. Emulsification.
10. Transformation of chemical compounds and crystal structures.
11. Destruction of bacteria.
12. Stimulation of plant growth.
13. Killing of small animals.
14. Formation of the basis for systems of television, underwater signaling, depth sounding, communication, etc.
15. The testing of materials and seismic exploration.

The ability to produce a highly directive and focused beam of vibration and to concentrate high powers in a small area makes most of these applications possible.

Thanks are due to Samuel Pines, with whom certain parts of the work was discussed, and to Anita Salisbury for typing and criticizing the manuscript.

NEW YORK, N.Y.
*February,* 1949

BENSON CARLIN

# CONTENTS

PREFACE . . . . . . . . . . . . . . . . . . . . . . . . . . . . . vii

*Chapter I*

ULTRASONIC WAVES . . . . . . . . . . . . . . . . . . . . . . . . . 1

Ultrasonics. Wave motion. Types of waves. Longitudinal waves. Shear waves. Surface or Rayleigh waves. Transformation of waves. Plane and spherical waves. Rectilinear propagation. Beams. Experimental examination of the beam. Velocity. The measurement of velocity in solids. Velocities in liquids and gases. Frequency and wavelength. Superposition. Diffraction. Reflection between two materials. Reflection from an obstacle. Orientation. Refraction. Loss of energy in ultrasonics. Experimental measurements of energy. The balance method. The echo method. Ultrasonic signaling in the ocean. Ultrasonic propagation in air. Propagation through wires. Methods of generating ultrasonics. Detection of ultrasonic waves. Theory. Methods. Common ultrasonic definitions.

Complete

*Chapter II*

ULTRASONIC WAVES: FURTHER THEORY . . . . . . . . . . . . . . . 31

Curves. The wave: simple harmonic motion. Complex waves. Fourier analysis. Wave train. Theoretical discussion of types of ultrasonic waves and their velocities. Longitudinal waves. Shear waves. Rayleigh or surface waves. Angular transmission. The law of angular transmission. Wave transformations at angular incidence. Between two solids. Liquids to solids. Solids to liquids. Solids to gas (free surface). The diffraction of light. Diffraction: systems. Striation. Transmission through thin plates. Absorption: theoretical considerations. Classic theory. Motional impedance. Beats. Doppler effect. Cancellation effects. Cavitation.

*Chapter III*

CRYSTALS FOR ULTRASONIC USE . . . . . . . . . . . . . . . . . 55

X General. History. The quartz crystal. The piezoelectric effect. The reverse piezoelectric effect. Some theoretical considerations. Temperature coefficient. Harmonics. Crystal shapes. Design of the ultrasonic crystal. Longitudinal waves: X-cut crystals. Shear waves: Y-cut crystals. Design considerations for tourmaline. Surface-wave crystals. Directional characteristics of crystals. Crystal plating. Cleaning the crystals. Facings for crystals. Ultrasonic output. Crystal combinations. Compound oscillators. Indicator for elastic oscillations. Curved crystals to fit the work. Focusing ultrasonics with curved crystals. Testing crystals for ultrasonic activity. Rochelle salt. Other types of crystals. Cutting and grinding special crystals.

*Chapter IV*

CRYSTAL HOLDERS FOR ULTRASONIC USE . . . . . . . . . . . . 81

Preparing the crystal. Holders. The holder for impressing ultrasonics on solids: longitudinal waves. The button. Air-gap resonance. Crystal damping. Standoffs. Mechanical. Fillers. Spring mountings. Magnetic holders. Holders for angular propagation. Holders for transmitting through liquids into solids. Holders for shear or surface waves in solids. Support in the liquid. Beam interrupter. Tanks. Beam-limiting devices. Further considerations in solids. Coupling the crystal to the work. Matching the crystal. Holders for agitating liquids. Submarine signaling transducers. The cable connection. Lenses and reflectors for ultrasonic work. Holders for resonance testing. Interferometry. Holders for microscope use.

*Chapter V*

RESONANCE AND REFLECTION . . . . . . . . . . . . . . . . . . . 109

Resonance. Standing waves. Resonance thickness measurement. Testing materials by resonance. Exciting resonance. Acoustic impedance. Matching impedances. Standing-wave ratio. History. Submarine apparatus. Interferometry. Indicating resonance. The complete resonance system. The oscillator. Magnetostrictive resonance system. The Reflectogage. Drop tests. The elimination of standing waves in test systems. Varying frequency. Other methods. Pulsed systems. Limitations of resonance.

*Chapter VI*

CONTINUOUS-WAVE ULTRASONIC SYSTEMS . . . . . . . . . . . . 137

Continuous waves. Testing materials. History. The general continuous-wave system. The ultrasonic oscillator. Other generators. Ultrasonic receivers. Sonic or ultrasonic signaling. Signaling by ultrasonic carriers. Factors that control transmission. Methods of use. Signaling in the ocean. Tuning the transducers. Transmission at an angle. Some experiences with continuous-wave testing. Standing waves. Varying the oscillator frequency. Other methods of indication. Shielding.

*Chapter VII*

PULSED ULTRASONIC SYSTEMS . . . . . . . . . . . . . . . . . . 162

History. Radar. Seismic signaling. Sonar. Testing materials with pulsed ultrasonics. Hughes ultrasonic instrument. Pulsed systems. Electronic considerations. The pulsed ultrasonic tester. Sweep. Sweep operation. Delay circuits. Differentiation. Marker circuits. The cathode-ray tube. Pulse forming. Pulse generation. Gas tubes. The high-vacuum pulse. Ultrasonic receivers for pulsed energy. Methods of gating the receiver. Some considerations in ultrasonic testing.

*Chapter VIII*

ULTRASONIC AGITATION . . . . . . . . . . . . . . . . . . . . . 200

General. History. Generators. Holders and containers. Power output. Measurement of ultrasonic power. Coupling to the crystal. The magnetostrictive system. Other systems. Dispersion and coagulation. Degassing. Chemical effects. Biological effects. Metallurgical applications. Effects on gases.

*Chapter IX*

MAGNETOSTRICTION . . . . . . . . . . . . . . . . . . . . . . . . . 222

Miscellaneous effects. General. Controlling device for oscillators. Materials. Systems. The magnetostriction oscillator: the rod. Dimensions and frequency. Shape. Diaphragms. Temperature coefficient. Design of the oscillating system—electrical. Miscellaneous applications. Advantages.

*Chapter X*

PRACTICAL CONSIDERATIONS IN THE APPLICATION OF ULTRASONICS . . . . . . . . . . . . . . . . . . . . . . . . . 243

Testing materials for flaws. Distance tested. Materials tested. Types and size of flaws. Size. Orientation. Wall thickness. Absorption testing. Shape. Surface. Use as a test instrument. Testing raw materials. Testing semifinished parts. Testing finished materials. Fatigue testing. Advantages and disadvantages of ultrasonic testing. Possible theoretical applications. Technique for close testing. Setting standards for ultrasonic testing. Measuring thickness by ultrasonics: resonance. The transmission of continuous ultrasonics. Ultrasonic agitation. Television. Signaling. Photographing cathode-ray screens. Medicine.

INDEX . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 265

# CHAPTER I

## ULTRASONIC WAVES

Ultrasonic waves have become of great importance in recent years. Their unique properties have been applied to industrial testing, signaling, medicine, and other fields.

**Ultrasonics.** Vibrational waves of a frequency above the hearing range of the normal human ear are referred to as *ultrasonic*, and the term therefore includes all those waves of a frequency of more than about 20,000 cycles. Since frequencies of as much as 500 mc[1] have been generated by methods recently developed, it is readily apparent that the term defines a tremendous range in both frequency and wavelength. Some of the vibrations that are of the same order of frequency as the audible ones act essentially in the same manner as they do; others in the minimum order of wavelength seem to behave like light. Many phenomena, especially those occurring in these higher frequency ranges, are still unexplained, and there are also numerous places where the classic theory and the observed facts do not agree.

In the minimum frequency range the length of ultrasonic waves in solids is about 8 in., in liquids about 2.4 in., and in gases about 0.63 in.

In the maximum frequency range the wavelengths approach a value in solids of $3.2 \times 10^{-4}$ in., in liquids one of $1 \times 10^{-4}$ in., and in gases one of $0.24 \times 10^{-4}$ in. It is possible that waves of even greater frequency and therefore shorter wavelength may be produced in the future.

Frequencies of 20,000 to 100,000 cycles are used for sound ranging, submarine signaling, and communication. Those of 100,000 to 10,000,000 cycles are used in testing materials for flaws. All frequencies are suitable for the investigation of the physical properties of matter. A more complete spectrum of frequencies and phenomena is shown in Table 1-1.

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[1] Bergmann, "Der Ultraschall," Berlin, 1942; translated by H. S. Hatfield, "Ultrasonics and Their Scientific and Technical Applications," Wiley.

TABLE 1-1. ULTRASONIC SPECTRUM

| Frequency, kc | Action |
|---|---|
| 20 | The upper limit to average human hearing. The boundary between sonics and ultrasonics. Common frequency for magnetostriction units for underwater work. Low-frequency underwater signaling, aerosol reactions, and agitation of liquids occur at or below this frequency |
| 25 | Ultrasonic control apparatus, door opening, etc. |
| 30 | Upper limit produced by friction |
| 40 | Common for underwater signaling |
| 50 | Through testing of materials in a liquid bath |
| 60 | Practical limit to generation by magnetostriction, blind-guidance devices |
| 90 | Top limit for tuning forks |
| 100 | Limit for Galton whistle |
| 120 | Limit for gas whistles in air |
| 300 | Thick limit on resonance testing by fundamental means. Limit to generation by spark discharge. Emulsion formation |
| 400 | Common frequency in emulsion and agitation work |
| 500 | Low limit, Reflectoscope. Upper limit to under-water signaling. Testing of material of large grain or poor homogeneity |
| 600 | Split high polymers |
| 750 | Experimental biological work |
| 1,000 | Common test frequency for materials with ordinary metallic structures. Production of oil jets |
| 2,250 | Common test frequency for material with fine grain structure |
| 5,000 | High limit, Reflectoscope. Testing of very fine homogeneous material |
| 6,000 | Thin limit, Reflectogage. Approximately 0.025 in. in steel |
| 7,500 | Mercury delay lines |
| 15,000 | Radar trainer, absorption measurements, delay lines |
| 500,000 | Highest ultrasonic frequency reported attained at the present |

The minute size of the ultrasonic wavelength is the factor that has made possible the application of these waves in many cases.

**Wave Motion.** Study of any recent text on physics or acoustics will give the modern concept of wave motion. Generally speaking, the term connotes a condition that is somehow transmitted so that it can be experienced at a distance from where it was originally generated. Ultrasonic waves are special forms of these general ones, in which the condition being propagated is a displacement of the particles of the medium in which the wave travels.

By placing a source of vibration in a bell jar and gradually evacuating the jar, it can readily be shown that these waves will not travel unless there is a medium through which they can be propagated. It can therefore be stated that the presence of a medium is essential to the transmission of ultrasonic waves.

Any material that has elasticity can propagate ultrasonic waves. The propagation takes the form of a displacement of successive elements of the medium. If the substance is elastic, there is a restoring force that tends to bring each element of material back to its original position. Since all such media also possess inertia, the particle continues to move after it returns to the position from which it started and finally reaches another different position, past the original one. From this second point it returns to its starting position, about which it continues to oscillate with constantly diminishing amplitude. The elements of material will therefore execute different movements or orbits as the wave passes through them. It is the differences in these movements which characterize basic types of ultrasonic waves; but no matter what the wave type, the general properties of ultrasonics remain.

As the wave travels through the material, successive elements in it experience these displacements, each such element in the wave path moving a little later than its neighbor. In other words, the phase of the wave, or vibration, changes along the path of wave transmission. This displacement can be plotted, and the graph is descriptive of the wave.

**Types of Waves.** An ultrasonic wave being transmitted through a substance may be any of several types. Each type causes a specific movement in the elements of the medium, and the paths that these elements follow as they move in response to the wave are called their *orbits.* These orbits may be essentially parallel to the line of propagation, in which case the wave is *longitudinal.* On the other hand, they may be executed normal to the direction of propagation. Such waves are called *transverse* or *shear* (usually shear).

Waves are also sometimes described on the basis of whether or not they change the volume of the material in which they are propagated. If they do, they are called *waves of dilatation;* and if they do not, they are classed as *waves of distortion.* Waves of dilatation are also usually classified as *irrotational.* This term defines a condition in which there is no element of rotation.

Longitudinal or shear waves may theoretically be either dilatational or distortional. However, a material cannot always support the propagation of all these types of wave motion, and those longitudinal waves used in ultrasonic applications are experimentally determined to be almost exclusively dilatational, while the shear waves are distortional. Therefore, longitudinal, dilatational, irrotational waves may be referred to as simply longitudinal, while shear, distortional waves may be called simply shear.

The type of wave should not be confused with the modulation impressed upon it. Any of these types may be continuous, modulated, or pulsed. They can be produced or detected by various means. None of these factors affect the general type.

*Longitudinal Waves.* Longitudinal waves exist when the motion of the particles in a medium is parallel to the direction of wave propagation. This kind of wave is also referred to as the *L* wave. The *L* type has been most often used in ultrasonics up to the present, since it will travel in liquids, solids, or gases and is easily generated and detected. Longitudinal waves have a high velocity of travel in most media, and the wavelengths in common materials are usually very short in comparison with the cross-sectional area of the transducer, the element that produces the waves. This property allows the energy to be focused into a sharp beam from which it diverges only slightly.

FIG. 1-1. Total vibration of a part due to internal waves.

The *L* wave should not be confused with the total vibration of a part in which ultrasonic or sonic waves are traveling. Such vibrations are characteristic of the geometry of the part and are caused by the action of waves within it (Fig. 1-1).

Since longitudinal waves exist within a comparatively small section of a part, they may or may not extend to the surfaces parallel to the direction of travel. However, it is not usual for them to reach such a boundary. Such waves are diagrammatically represented in Fig. 1-2.

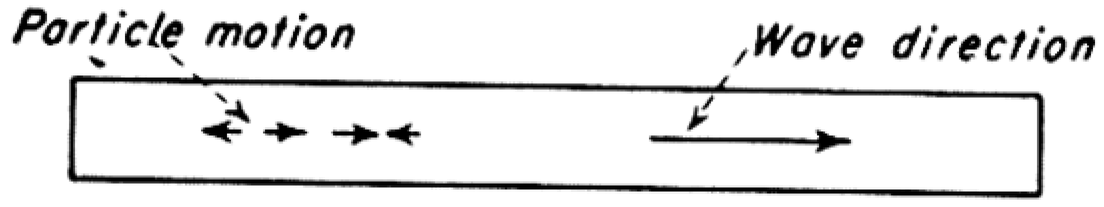

FIG. 1-2. Longitudinal waves traveling through a medium.

Longitudinal waves may be generated within a medium by the vibration of any one of its surfaces in a normal direction and at an ultrasonic frequency. If the energy is to remain in a beam, the frequency (and therefore the wavelength) must be the proper ratio to the area of the surface that is being vibrated.

In order to make use of these oscillations, since they travel with very great velocities, and since their frequencies are generally high, the systems that are used with them must be capable of responding to such frequencies and of resolving signals following each other closely in time. In those cases where time intervals are to be determined, means of measuring to the nearest microsecond are necessary.

*Shear Waves.* When shear waves are used, the movement of the particles in the medium is at right angles to the direction of wave propagation. If the wave movement is in the $x$ direction, the particle displacement is in the $y$ direction. These waves may also exist either in a limited area of or entirely throughout a body. Usually, however, they are in the form of a beam of small cross section in comparison with the cross-sectional area of the piece in which they travel. The beam does not ordinarily extend to a surface parallel to the direction of travel. Shear waves, which will also be referred to hereafter as $S$ waves, have a velocity that is approximately one-half of that of the $L$ waves. Because of ~~this lower velo~~city, the wavelength of shear waves is much shorter than that of $L$ waves. Figure 1-3 illustrates the particle motion in a shear wave.

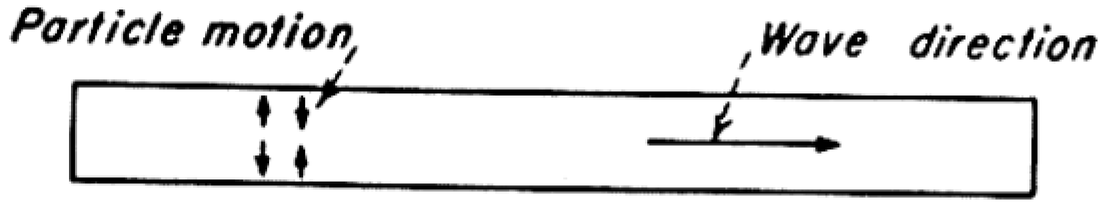

FIG. 1-3. Particle motion and wave direction of a shear wave.

Shear waves have certain advantages, because their lower velocity makes the electronic timing circuits with which they are used less critical. However, the shorter wavelength makes them more sensitive to small inclusions, and they are therefore more easily scattered within a material. Moreover, since the vibration is in a specific direction, rotation of the sending element changes this direction, and therefore polarization effects may be noticed. In other words, the results in a material that is not absolutely uniform may differ with rotation of the transducer. Shear waves will not travel in liquids or gases, since there is no elasticity to shear in such materials.

Shear waves are generated by applying a shearing force to the face of a material, *i.e.*, rocking it back and forth in a direction parallel to the surface. The whole part may also vibrate in a shear manner (Fig. 1-4).

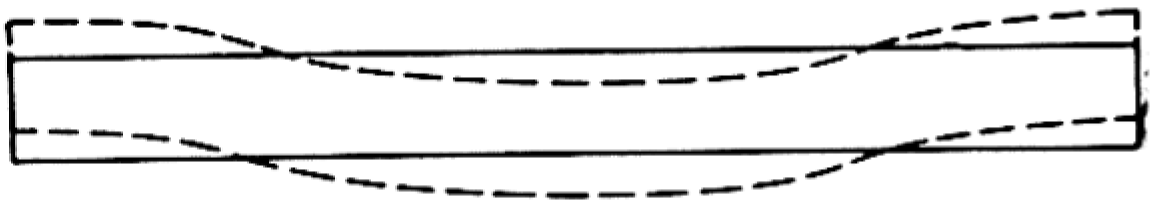

FIG. 1-4. Total shear motion of a part.

*Surface or Rayleigh Waves.* Waves can be propagated over the surface of a part without penetrating below that surface to any extent. These waves are roughly analogous to water waves which travel over a body of water. Their velocity depends upon the material itself and is about nine-tenths of $S$-wave velocity.

Surface waves can be generated by shaking an area of a surface back and forth in a manner similar to that by which $S$ waves are generated. However, the area is oblong in shape.

The wavelength of a surface wave is always extremely short, and the plate on which it travels is at least several wavelengths thick. Under such conditions the displacement of particles a few wavelengths below the surface is negligible. Surface waves consist of both $L$ and $S$ types of particle motion. Figure 1-5 is a representation of surface waves traveling over a plate.

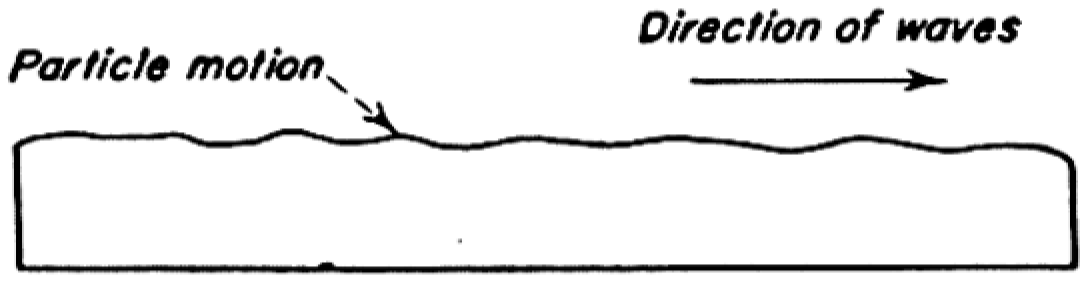

FIG. 1-5. Surface wave traveling over a plate.

Any of these wave types can be used for exploration of materials for defects, for measuring thickness by resonance or other methods, for measuring characteristics of the material in which the wave travels, or for performing any of the other functions of which ultrasonic waves are capable.

**Transformation of Waves.** When a wave of any kind strikes a boundary between two media of different acoustic impedances at an angle other than 90 deg, a transformation may take place and the wave may be changed into another type. The theoretical conditions for such a transformation are discussed elsewhere (Chap. II).

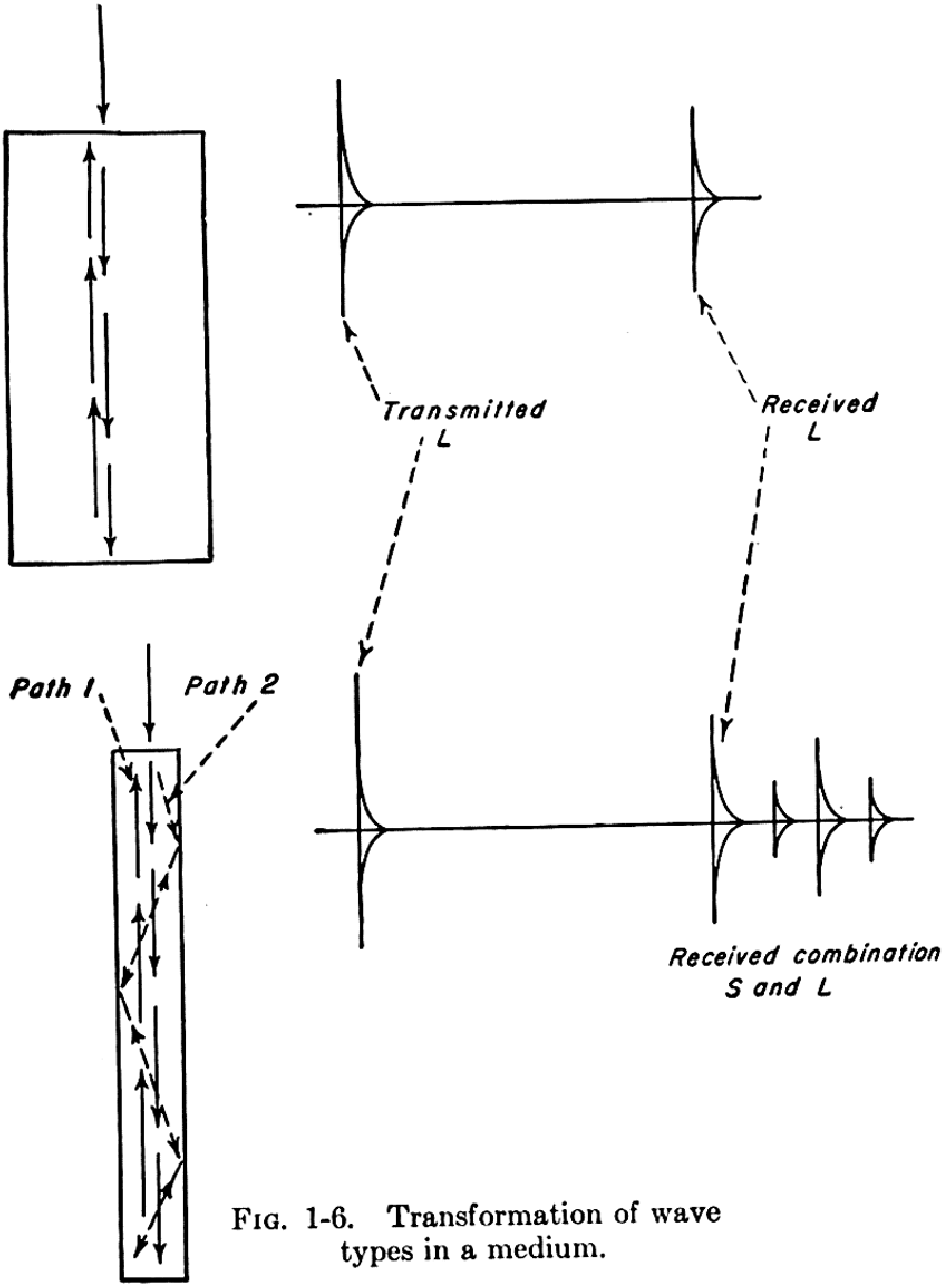

FIG. 1-6. Transformation of wave types in a medium.

However, a common example would be an *L* wave passing from a liquid to a solid and hitting the solid at an angle. At the boundary between the liquid and solid, reflected *L* and *S* waves and transmitted *L* and *S* waves may form with different amplitudes and different angles of travel, depending on the angle at which the wave hits and also on the impedances of the materials. Since *S* waves will not travel in liquid, only the reflected *L* wave and the transmitted *L* and *S* waves remain. Thus, under certain appropriate conditions the type of wave may be changed. Figure 1-6 shows diagrammatically what may happen when an *L* wave undergoes such a transformation.

Changes such as these can be very misleading to an investigator who does not take into account all the types of waves that may appear at such a boundary. It should also be noted that in the case of liquids incident on solids, the results will be misleading unless the liquid wets the solid. Wetting agents may be included to assist in obtaining intimate contact.

The case of liquids incident upon solids is of practical interest in studying earthquakes and in the design of transducers where a volume of liquid is imprisoned between the transducer and the medium. It is also of concern in testing objects that are inspected in a liquid bath.[1,2]

Waves traveling in a metal or solid part supported in air exhibit the same tendency, and a number of misleading signals will be observed, which are caused by the originally generated wave hitting a boundary at an angle. This results in the generation of different types of waves, which, in turn, again hit a boundary and repeat the phenomenon. In this way a large number of extraneous signals may be generated, each traveling at its own velocity and in a different direction. When observed on a receiver, the resulting signal is so confused that it is impossible to interpret.

A part whose dimensions are such that waves are likely to strike a boundary at an angle will cause the transformation of wave energy. Thin or irregularly shaped sections are particularly apt to produce such an action.

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[1] Macelwaine and Sohon, "Introduction to Theoretical Seismology," Wiley, 1932.

[2] Knott, *London, Edinburgh, Dublin Phil. Mag.*, **48**, (5th ser.), 64-97, July–December, 1899.

**Plane and Spherical Waves.** Ultrasonic waves may usually be considered as essentially plane; *i.e.*, the amplitude of motion over a plane perpendicular to the direction of wave travel is uniform. As a result, the orbits of the elements are in a straight line instead of being elliptical or circular. The size of the vibrating area and the distance that the waves have traveled both affect the shape of the wave front. Generally as the distance of propagation increases, the wave becomes more nearly plane.

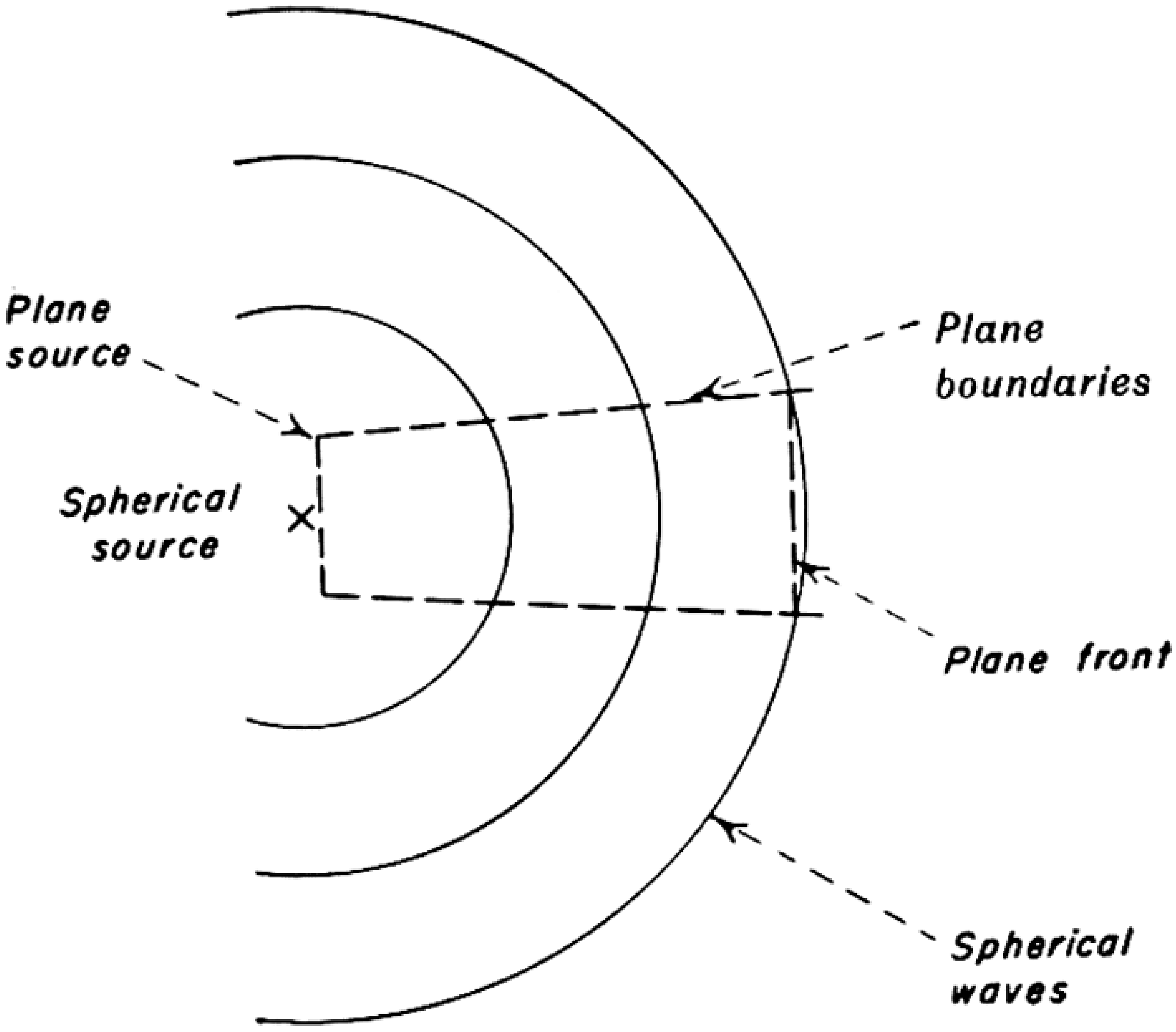

FIG. 1-7. Paths of plane and spherical waves.

A purely spherical wave is one produced by a point source, from which it spreads out evenly in all directions. Since the control of wave direction is important, such waves are rarely used in practice except in the theoretical consideration of ultrasonic effects and in certain specialized applications. The difference between a plane and spherical wave is illustrated in Fig. 1-7.

**Rectilinear Propagation.** Rectilinear propagation is a characteristic exhibited by ultrasonic waves because of their short wavelength. In such a case the wave motion is transmitted in a straight line. Therefore, energy cannot travel around sharp discontinuities. It is this property which makes it possible to use these waves for locating small objects, since any such small inhomogeneity will cast a sharp shadow behind it.

As the wavelength becomes shorter and shorter, the wave motion more closely approaches the ideal condition of absolute rectilinear propagation. However, the characteristic is pronounced enough to be evidenced at almost all ultrasonic frequencies.

**Beams.** A beam of ultrasonics is propagated through a material with very little divergence. Although such a beam can be considered to be confined to the projection of the face of the transducer, in reality there is always some spreading. This spread is a function of the ratio $\lambda/D$, where $\lambda$ is the wavelength of the ultrasonic wave and $D$ is the distance across the transducer face.

In an ordinary quartz plate the energy is located in a cone whose half angle of spread is given by

$$\sin A = 1.2 \frac{\lambda}{D}$$

This formula will not give exact experimental results, because the way in which the crystal is mounted affects its beaming characteristics. For example, edge effects may produce secondary beams.

These secondary rays are not determined by the relation above but have greater angles of spread. However, in practical work the basic beam is the only one of consequence.

When ultrasonic waves hit the face of a material in which they are to be propagated, only the main beam will be transmitted through the interface and actually enter the medium, since the transmitted energy depends on the angle at which the waves hit. There is such great refraction in the ordinary case of an oil-to-metal surface that any beam diverging at more than a comparatively small angle is totally refracted. This angle is about 15 deg from the normal and is determined in the usual way by the ratio of the velocities of the ultrasonics in the two media, the one from which the waves are transmitted and the one that they enter (Fig. 1-8). The figure shows how parts of a beam hitting at an

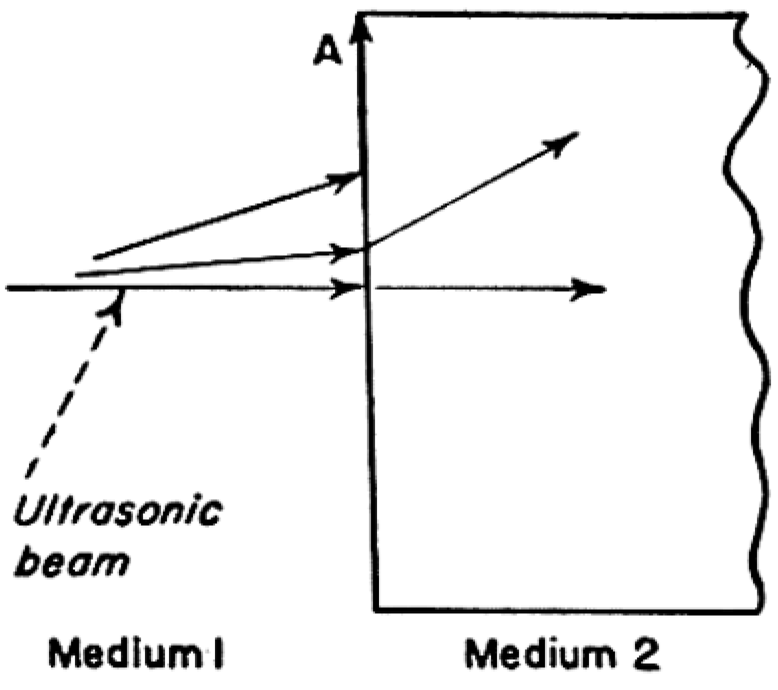

FIG. 1-8. Action of a wave at a boundary.

angle greater than the critical value are bent so much that they do not cross the interface. In the figure, *A* represents such a refracted ray.

The beam may be scattered in other ways than by its normal divergence. For example, if the medium in which it travels is full of small dispersed discontinuities or is of very large grain size, the ultrasonic energy will be broken up and reflected and refracted in a haphazard manner. This may occur even between neighboring crystals of different elastic properties. In this way the energy may be diffused by continuous reflection.

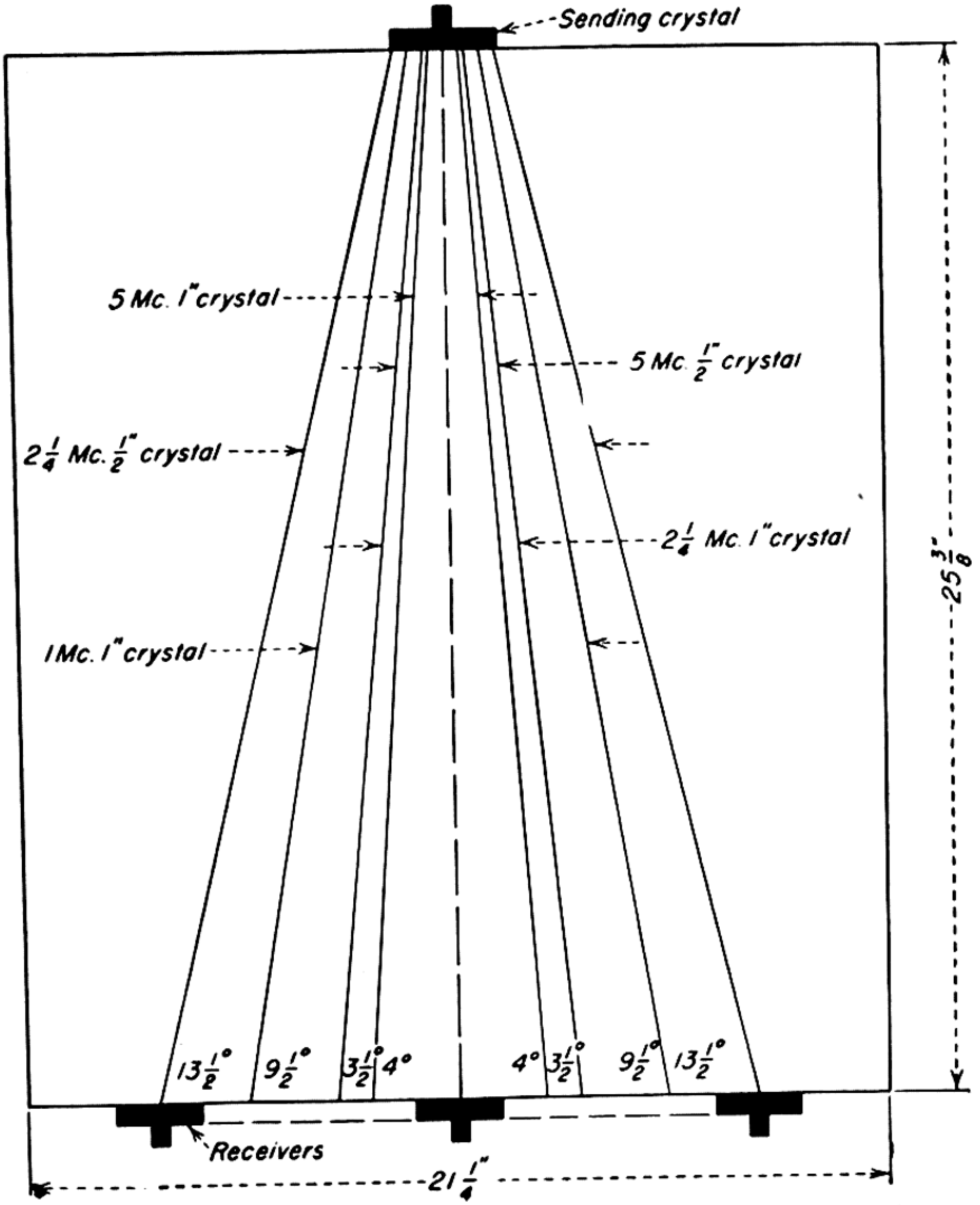

FIG. 1-9. Beam spread at various frequencies from a given transducer size.

This difficulty can be minimized by lowering the frequency of transmission, thus initially widening the beam. However, because of the now longer wavelength, the energy will not be affected by the small discontinuities but will pass through them without reflection. In other words, with a given transducer size, the beam spread becomes greater as the frequency goes down but the internal scattering becomes less. However, the size of the usual transducer is large enough so that the sharpness of the beam is still maintained even at the lower frequency.

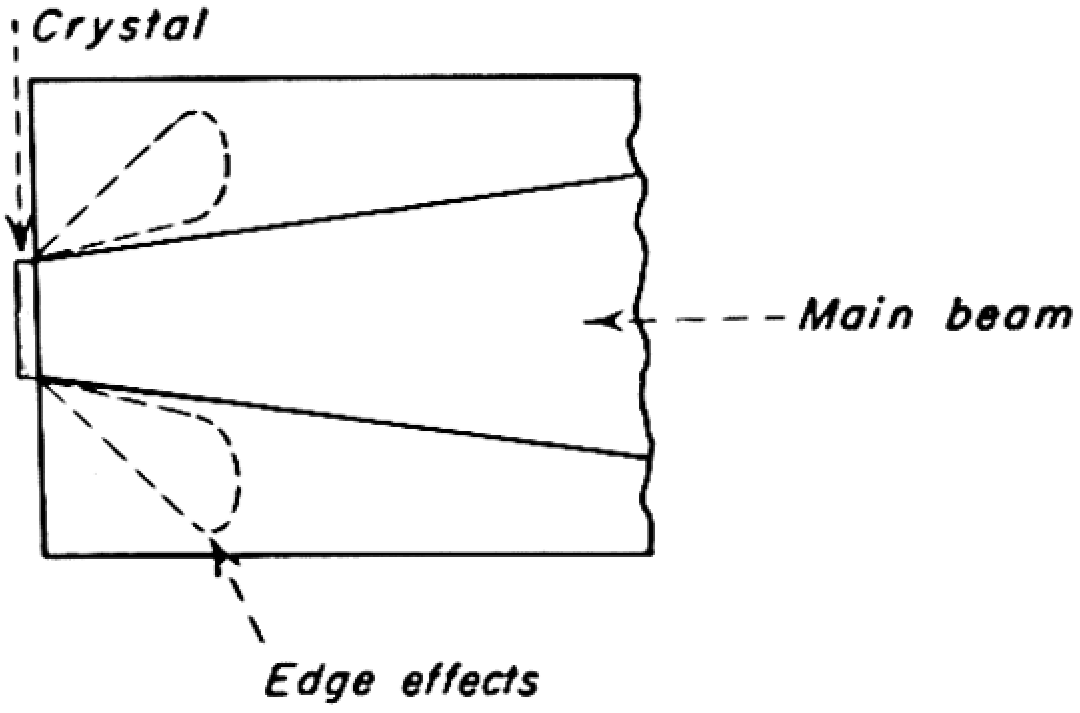

FIG. 1-10. Secondary beams resulting from mounting effects.

Besides the normal beaming effect, many special means have been tried for focusing the beam of ultrasonics more sharply. Some of these means are discussed in the later context.

Figure 1-9 shows the way in which beams of ultrasonic energy of different frequencies fan out from a vibrating body. Figure 1-10 shows the possible effects of the mounting in producing secondary lobes.

**Experimental Examination of the Beam.** The distribution of the ultrasonic energy in a beam can be explored experimentally in several ways. One such way is shown in Fig. 1-11. In this case the energy is sent out by a crystal and is transmitted through a medium. A second crystal is used as a receiver on the opposite side of the medium to explore the field and determine its intensity. The amplitude can then be read at several points and plotted. By changing the thickness of the medium, the beam can be explored at various distances from the sending crystal.

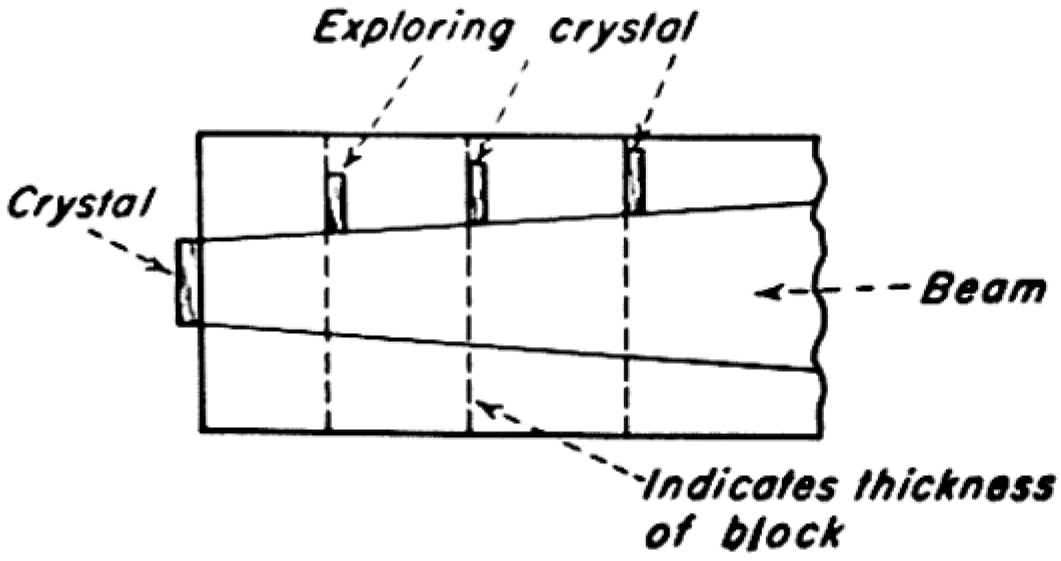

FIG. 1-11. Method of exploring beam spread.

**Velocity.** There are a number of different types of velocity that can be discussed. The most significant are referred to as *phase velocity*, *group velocity*, and *signal velocity*.

Each of these terms covers a complex phenomenon, and they should not be confused with each other or with the velocity of the particles in the waves as they execute their orbits.

The phase velocity may be defined as the speed with which a phase is "propagated" along a wave. It refers to a condition existing along the line of propagation that seems to show a change in phase traveling along with and superimposed on the wave itself. Such a velocity is not of much practical interest in ultrasonics except in performing theoretical computations.

Group velocity is a term used to indicate the velocity with which the envelope of a wave is propagated when the wave is amplitude-modulated. The basic or carrier frequency must be high for such a condition to manifest itself.

The group velocity is most often considered in ultrasonic work. Whenever the term *velocity* is used without a modifier, group velocity is referred to. Phase and group velocity may have the same or different values. In the first case the material is not dispersive, and in the second it is.

A material is dispersive when signals of different frequencies travel with different velocities. It is not entirely established whether or not ultrasonic signals are dispersive under all possible conditions. However, the weight of evidence so far is that they are dispersive in solids and liquids.

Signal velocity is a very complex condition existing only when a medium is dispersive. In such a case different signals seem to travel with different velocities, and the actual speed of travel of a particular signal is its signal velocity. The time of travel may differ with the sensitivity of a receiver; and changing the sensitivity of a particular receiver may change the signal velocity.

The velocity of the wave and that of the individual particles of material are not the same. In all cases it is the velocity of the propagation of the wave that is referred to.

The group velocity is also referred to as bulk velocity in some contexts.

**The Measurement of Velocity in Solids.** A number of investigators, including the author, have experimentally measured the velocities of ultrasonic waves in various media. However, there are differences in published results. These may be due either to the equipment used or to phenomena that are so far unexplained. Apparatus that can be adapted to making such measurements will be described in the following chapters.

There is a possibility that velocity varies somewhat with intensity. Experiments indicate that velocity may be higher near the source, where the intensity of ultrasonics is very great. Under such conditions velocities as much as three times normal have been reported.[1] However, the frequency is not affected by the intensity.[2]

The velocity of longitudinal waves is given by the relation

$$c = \sqrt{\frac{E}{d} \frac{1 - \mu}{(1 + \mu)(1 - 2\mu)}}$$

where $E$ = Young's modulus
$c$ = velocity
$\mu$ = Poisson's ratio
$d$ = density

Examination of this formula shows that velocity depends on the density and elastic constants of the medium. Young's modulus may be defined as a relation between the stress intensity and the resulting strain. Poisson's ratio is the relation between a change in width and the change in length that causes it.

Common velocities of longitudinal waves in solids, liquids, and gases are given in Table 1-2.

The velocity of shear waves is given as

$$c = \sqrt{\frac{G}{d}}$$

where $G$ = modulus of rigidity

This velocity is about 48 per cent of that of the longitudinal one. Tables of shear-wave velocities can be computed from the longitudinal ones using this factor.

The velocity of Rayleigh or surface waves is (about)

$$c = 0.9 \sqrt{\frac{G}{d}}$$

It can be shown that the constant (numerical) multiplier changes with the properties of the medium.

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[1] Angerer and Fadenburg, *Ann. Physik.*, **66**, 293 (1933).

[2] Boyle and Taylor, *Trans. Roy. Soc. Canada*, **19**, 197 (1925).

TABLE 1-2. ULTRASONIC PROPERTIES OF COMMON MATERIALS

| Material | Velocity, cm/sec × $10^{+5}$ | Density, g/cu cm | Specific acoustic impedance × $10^6$ |
|---|---|---|---|
| Air | 0.331 | 0.00120 | 0.0000413 |
| Alcohol | 1.44 | 0.79 | 0.11 |
| Aluminum | 6.22 | 2.65 | 1.70 |
| Bakelite | 2.59 | 1.4 | 0.363 |
| Brass | 4.43 | 8.5 | 3.61 |
| Copper | 4.62 | 8.93 | 4.11 |
| Glass | 4.9–5.9 | 2.5–5.9 | 1.805 |
| Lead | 2.13 | 11.4 | 2.73 |
| Magnesium | 5.33 | 1.74 | 0.926 |
| Mercury | 1.46 | 13.6 | 1.93 |
| Nickel | 5.6 | 8.9 | 4.98 |
| Polystyrene | 2.67 | 1.1 | 0.294 |
| Quartz | 5.75 | 2.65 | 1.52 |
| Steel | 5.81 | 7.8 | 4.76 |
| Transformer oil | 1.39 | 0.92 | 0.128 |
| Water | 1.43 | 1.00 | 0.143 |

TABLE 1-3. WAVELENGTHS IN COMMON MATERIALS IN CENTIMETERS

| Material | Frequency, mc | | | |
|---|---|---|---|---|
| | ½ | 1 | 2¼ | 5 |
| Air | 0.0688 | 0.0344 | 0.0153 | 0.00688 |
| Aluminum | 1.244 | 0.622 | 0.277 | 0.124 |
| Bakelite | 0.518 | 0.259 | 0.115 | 0.0518 |
| Brass | 0.886 | 0.443 | 0.197 | 0.0886 |
| Copper | 0.924 | 0.462 | 0.206 | 0.0924 |
| Glass | 1.040 | 0.520 | 0.231 | 0.104 |
| Lead | 0.426 | 0.213 | 0.0947 | 0.0426 |
| Magnesium | 0.533 | 0.267 | 0.119 | 0.0533 |
| Mercury | 0.284 | 0.142 | 0.0631 | 0.0284 |
| Polystyrene | 0.534 | 0.267 | 0.119 | 0.0534 |
| Quartz | 1.150 | 0.575 | 0.255 | 0.115 |
| Steel | 1.162 | 0.581 | 0.259 | 0.116 |
| Transformer oil | 0.278 | 0.139 | 0.0618 | 0.0278 |
| Water | 0.290 | 0.145 | 0.0645 | 0.0290 |

**Velocities in Liquids and Gases.** Only $L$ waves can be transmitted in liquids and gases. In such cases it is usually assumed that the vibrations take place too rapidly for heat to exchange. The velocity in either a liquid or gas is then[1]

$$c = \sqrt{\frac{K}{\rho B_{is}}} = \sqrt{\frac{1}{\rho B_{ad}}}$$

where $K$ = ratio of specific heats
$B_{is}$ = compressibility at a constant temperature
$B_{ad}$ = adiabatic compressibility

Measurements of velocities are made in liquids in order to get an idea of their chemical and physical characteristics. A large number of such measurements have been made and will be found in the literature.

Two main methods of measurement are used. The interferometer is used for both liquids and gases.[2] Pulse methods have been more recently applied, and the time of travel of a pulse measured.[3]

In any of these formulas any consistent system of units may be used.

**Frequency and Wavelength.** The usual relation among frequency, velocity, and wavelength holds for ultrasonic waves. They are related as

$$\lambda = \frac{c}{f}$$

where $\lambda$ = wavelength
$c$ = velocity
$f$ = frequency

Common wavelengths are given in Table 1-3 and a nomograph of the formula in Fig. 1-12, from which the third value can be read when two are known.[4]

**Superposition.** It can be shown theoretically that the same section of a medium may concurrently transmit a number of different waves, which do not interfere with each other in motion and which travel individually. These can therefore be considered as completely independent and separate.

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[1] Bergmann, *op. cit.*

[2] G. W. Pierce, *Proc. Am. Acad. Arts Sci.*, **60**, 271 (1925).

[3] F. A. Firestone, U.S. Patent 2,398,701.

[4] B. V. Henvis, Wavelengths of Sound, *Electronics*, March, 1947.

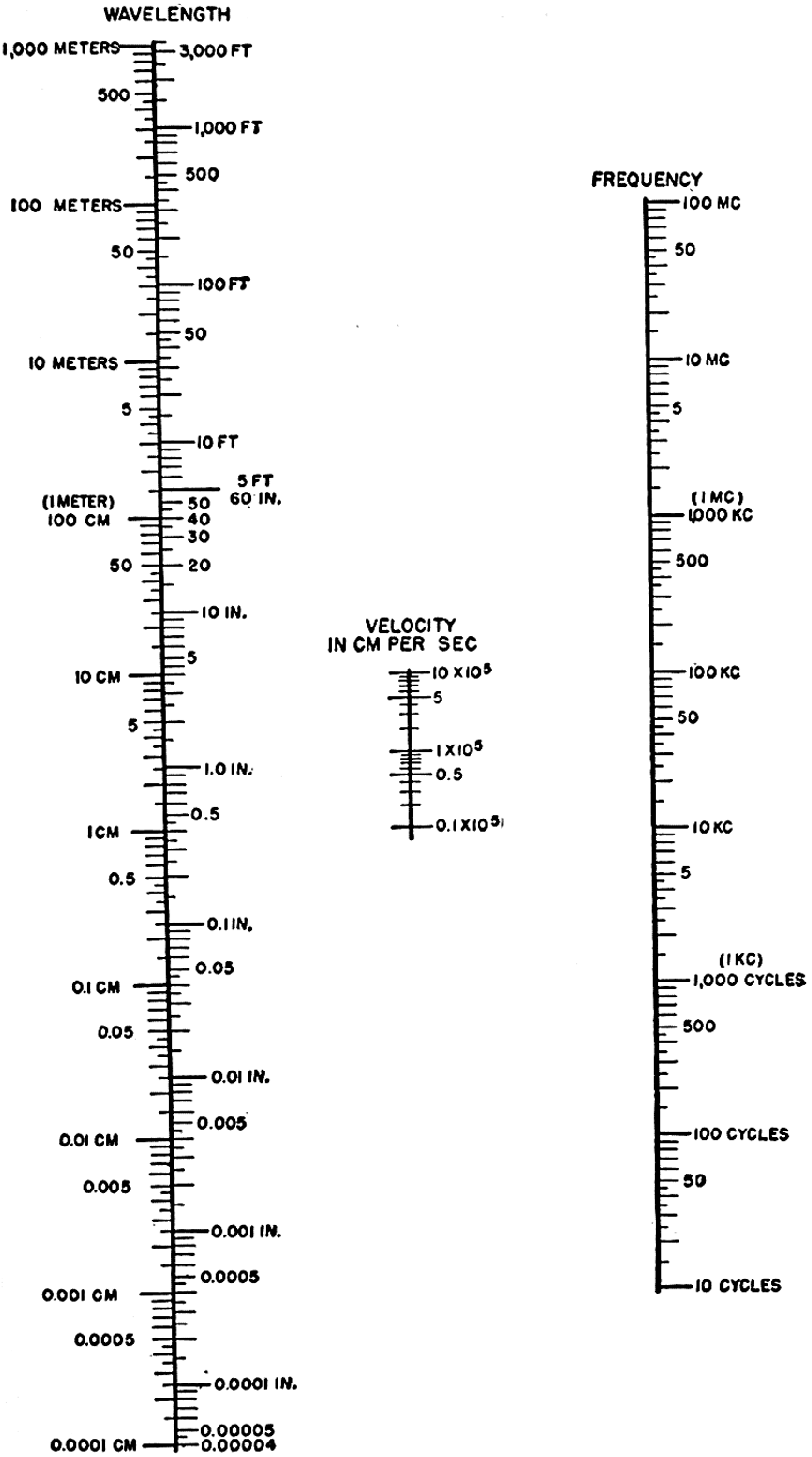

Fig. 1-12. Nomograph relating frequency, wavelength, and velocity.

However, if an ordinary ultrasonic indicator were placed on the material, the sum of all the wave displacements would be shown. The wave pattern becomes very complicated, and it is impossible to separate out all the various components and view each one separately. It is, however, possible that the complicated pattern itself can be taken as an indication of the condition of the medium.

**Diffraction.** Ultrasonic waves do not always propagate in a rectilinear manner. For example, a wave passing near the edge of an object has a tendency to become bent toward and around it. This bending of the wave is called *diffraction.* Ultrasonic signals that would normally be received at a certain point may be diverted by diffraction and received at some other position.

**Reflection between Two Materials.** When a wave traveling through one material impinges on a boundary between it and a second medium, part of the energy travels forward as one wave through the second medium while part is reflected back into the first medium, usually with a phase change.

The characteristic that determines the amount of reflection is known as the *specific acoustic impedance* and is the product of the density and velocity. The amplitude of the reflected wave is related to the incident one as

$$A_r = \frac{R_1 - R_2}{R_1 + R_2}$$

where $R_1 = \rho_1 c_1$
$R_2 = \rho_2 c_2$
$\rho$ = density of each material
$c$ = velocity
$A_r$ = amplitude of the reflected energy

The subscripts 1 and 2 indicate two media. Any system of units can be used.

As long as the wave travels in the same medium, the energy is proportional to the amplitude squared. Therefore,

$$R = R_0 \left( \frac{\rho_1 c_1 - \rho_2 c_2}{\rho_1 c_1 + \rho_2 c_2} \right)^2$$

where $R$ = reflected energy
$R_0$ = incident energy

In the case of an air-solid boundary, practically 100 per cent of the energy is reflected.

It should be remembered that in a reflection system, the energy passes through an interface twice, once going and once returning. For a liquid-steel interface about 88 per cent is reflected each time. Thus the energy received after two transmissions through the boundary is 12 per cent of 12 per cent, or 1.4 per cent.

All these calculations are entirely independent of attenuation and scattering. The amount of energy actually reflected may differ vastly from that calculated theoretically. Energy may be dissipated at a boundary or in a material in several ways. The formulas given refer only to an absolutely perfect boundary between two infinite media. If there is any discontinuity, no matter how minute, these relationships no longer apply. It is accordingly difficult to get actual values of reflected energy except by experiment.

A table of values of reflection between two media is shown in Table 1-4, and a graph of per cent reflection in Fig. 1-13.[1]

Strong reflections take place when transmitting from any liquid to any solid. However, the usual way of getting ultrasonic waves into a solid is by using thin films of couplants (usually liquids), since air boundaries reflect almost 100 per cent. In such a case the energy equation becomes

$$\frac{R}{R_0} = \frac{\left(\frac{R_1}{R_2} - \frac{R_2}{R_1}\right)^2}{4 \cot^2 \frac{2\pi L}{\lambda} + \left(\frac{R_1}{R_2} + \frac{R_2}{R_1}\right)^2}$$

The thickness of films capable of reflecting different amounts of energy can be calculated from this for various wavelengths, and optimum thicknesses chosen for coupling layers.

Most reflections in a medium take place from obstacles of irregular shape, size, and orientation. Some of the considerations in such a case are discussed elsewhere. However, it is impossible to calculate most such effects. If the surface is flat and large with respect to the wavelength, the reflection is essentially specular. A flat surface may be considered one where the

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[1] F. W. Smith and P. K. Stumpf, Ultrasonic Generator, *Electronics*, April, 1946.

Table 1-4. Per Cent Reflection of Ultrasonic Vibrations Normally Incident to the Boundaries between Various Media Perfectly Joined at Interface

| Material or medium | Specific acoustic impedance $\times 10^6$ | Aluminum | Steel | Nickel | Magnesium | Copper | Brass | Lead | Mercury | Glass | Polystyrene | Bakelite | Water | Oil | Air |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aluminum | 1.70 | 0 | 21 | 24 | 9 | 18 | 14 | 3 | 1 | 2 | 50 | 42 | 72 | 74 | 100 |
| Steel | 4.76 | ...... | 0 | 0.2 | 43 | 0.3 | 1 | 9 | 16 | 31 | 77 | 76 | 88 | 89 | 100 |
| Nickel | 4.98 | ...... | ...... | 0 | 47 | 0.8 | 2 | 12 | 19 | 34 | 79 | 75 | 89 | 90 | 100 |
| Magnesium | 0.926 | ...... | ...... | ...... | 0 | 40 | 36 | 20 | 12 | 2 | 27 | 19 | 54 | 58 | 100 |
| Copper | 4.11 | ...... | ...... | ...... | ...... | 0 | 0.2 | 7 | 13 | 19 | 75 | 71 | 87 | 88 | 100 |
| Brass | 3.61 | ...... | ...... | ...... | ...... | ...... | 0 | 5 | 10 | 23 | 73 | 68 | 86 | 87 | 100 |
| Lead | 2.73 | ...... | ...... | ...... | ...... | ...... | ...... | 0 | 1 | 9 | 62 | 55 | 79 | 80 | 100 |
| Mercury | 1.93 | ...... | ...... | ...... | ...... | ...... | ...... | ...... | 0 | 4 | 8 | 6 | 75 | 76 | 100 |
| Glass | 1.805 | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | 0 | 40 | 32 | 65 | 67 | 100 |
| Polystyrene | 0.294 | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | 0 | 1 | 12 | 17 | 100 |
| Bakelite | 0.363 | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | 0 | 18 | 23 | 100 |
| Water | 0.143 | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | 0 | 0 | 100 |
| Transformer oil | 0.128 | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | 0 | 100 |
| Air | 0.0000413 | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | 0 |

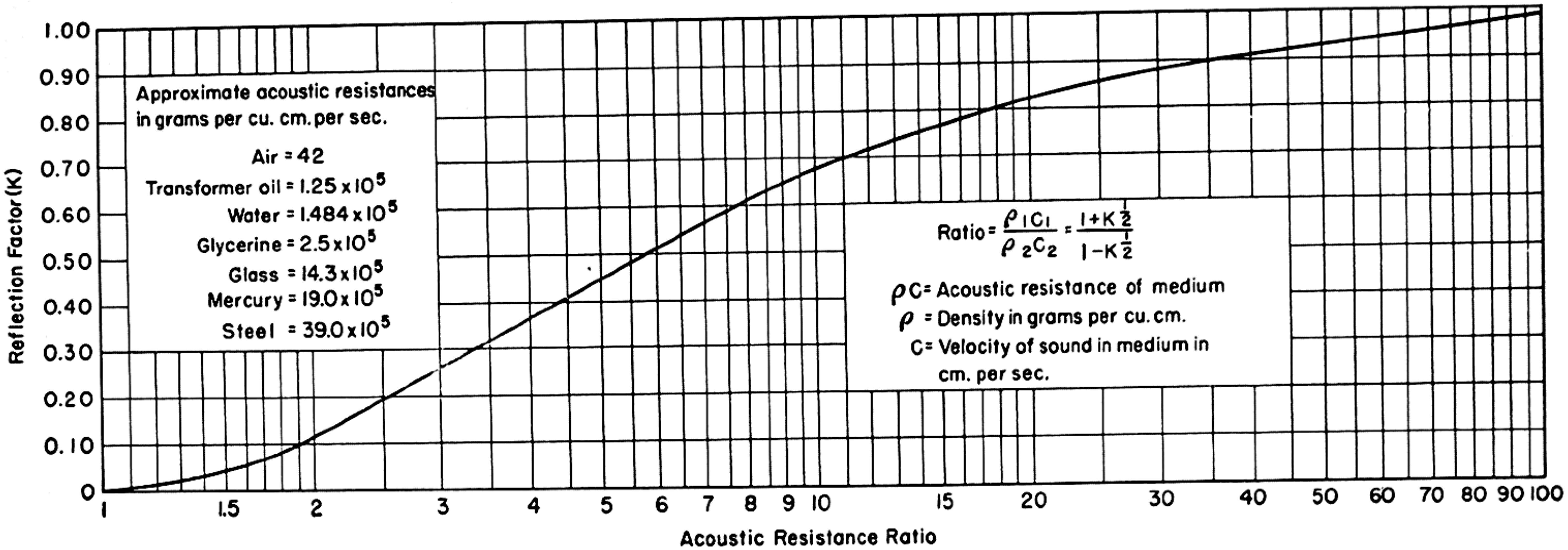

FIG. 1-13. Reflection of waves at a boundary.

irregularities are not greater than about $\frac{1}{20}\lambda$. When the surface is very irregular, the energy is broken up and reflected haphazardly.

**Reflection from an Obstacle.** When an ultrasonic wave meets an obstacle, it may be reflected in various ways depending upon both the nature of the obstacle and its size. The phenomenon is a very complex one and cannot be easily explained. The action seems to depend upon the relation of the wavelength and the size of the obstacle. If the obstacle is large compared with the wavelength, there is a strong reflected wave that returns from it. A definite shadow is cast behind the obstacle or defect, and there may or may not be some diffraction of the wave around its edges. If the obstacle, however, is very small and only a very small fraction of a wavelength, there will be no real reflection and no shadow. The ultrasonic energy seems to pass around the obstacle and to come together behind it and pass along as though there were no interference. Of course, if there are enough of these small inclusions or obstacles, a large proportion of the energy may be scattered but there will still be no reflection. The energy will merely disappear inside the piece, and it is difficult to say exactly why this is so.

One possible explanation of the phenomenon of such reflection is as follows: The wavelength of any ultrasonic vibrational wave represents the distribution of particle displacement within a certain limit: *i.e.*, it represents the amount of compression or expansion in any particular interval of the entire range covered by one wave. Thus, in a 1-mc wave the amount of compression covers an area of a half wavelength, or approximately $\frac{1}{16}$ in. in aluminum, while in a 5-mc wave the amount of compression covers an area of a half wavelength, or approximately $\frac{1}{80}$ in. in aluminum. The ratio of the size of the flaw to this wavelength represents the fraction of this compression which is interfered with by the obstacle. If an obstacle is $\frac{1}{50}$ in. in dimension, it will interrupt the entire 5-mc wave but only approximately $\frac{1}{16}$ of the 1-mc wave.

The dimensions mentioned so far are in the direction parallel to the propagation of the wave. Now, if this same flaw or obstacle has a very small cross-sectional area, this smallness coupled with the fact that it has a minute effect on the 1-mc wave will give negligible reflection. However, this same small flaw will completely interrupt a high-frequency wave over its area and will cause an appreciable reflection. The greater the cross-sectional area of the flaw the more energy it will interrupt and the larger the reflected signal will be.

In other words, there are two important factors that influence the reflection. One is the dimension in the direction along the propagation path; the other is the cross-sectional area. It is the dimension along the propagation path that interrupts the wave, but it is the cross-sectional area that determines the amount of reflection.

**Orientation.** The orientation of a reflecting surface is important, since it is essentially the projection of the interface on a plane perpendicular to the beam that determines the amount of reflection. A very regular interface, however, may act as a perfect reflector and direct the beam away at an angle, in the same manner that a beam of light is reflected by a mirror. Irregular surfaces almost always return some of the energy along the path by which it reached the obstacle.

**Refraction.** It is sometimes advisable to send ultrasonic waves into a medium at angular incidence. Materials or liquids of a wedge shape can be used for such purposes. When this is done, the ray is introduced at an angle $\theta_1$ and travels within the material at another angle $\theta_2$, the difference being caused by refraction at the interface (Fig. 1-14).

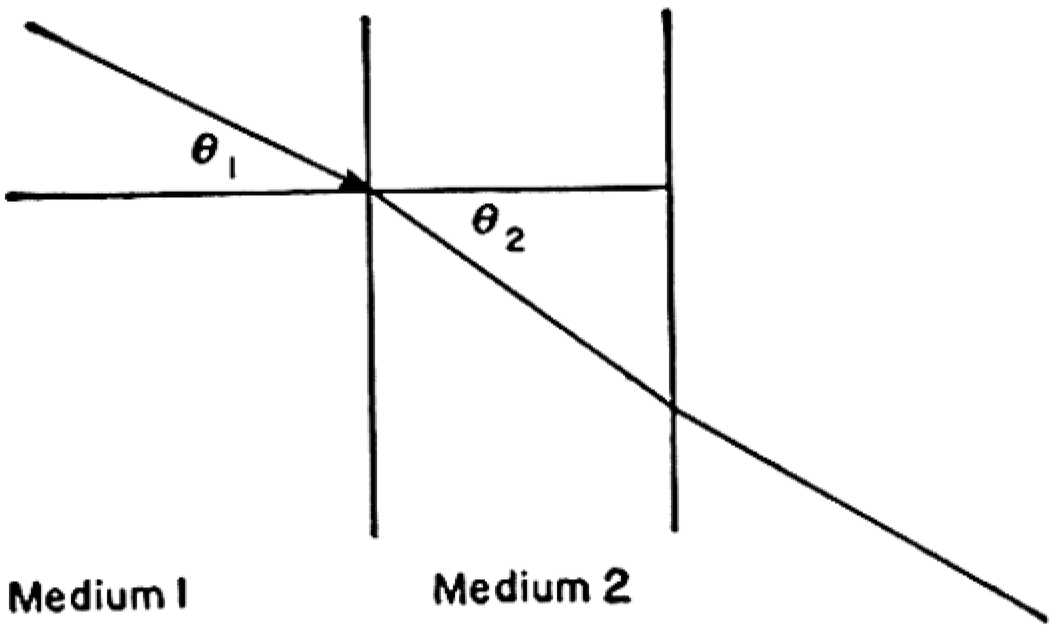

FIG. 1-14. Refraction at a boundary.

The angle of this refracted wave is

$$\frac{\sin\,\theta_1}{\sin\,\theta_2} = \frac{c_1}{c_2}$$

where $\theta_1$ = angle of incidence
$\theta_2$ = angle of refraction
$c_1$ = velocity in first medium
$c_2$ = velocity in second medium

When these angles are small, $\theta_1$ may be considered equal to sin $\theta_1$ and $\theta_2$ equal to sin $\theta_2$. Small angles of inclination will therefore be greatly magnified.

Total reflection at the interface occurs for values of $\theta_2$ equal to or greater than 90 deg. At that point

$$\sin \theta_1 = \frac{c_1}{c_2}$$

For liquids and solids $\theta_1$ is about 15 deg. Therefore when the angle of incidence is greater than this value, no energy at all enters the part.

When shapes are complex, refraction patterns become extremely hard to interpret. For example, in a part flat on one side and curved on the other, the ray enters the flat side with no refraction but exits from the curved one broken up so that various parts of it travel at different angles.

Lenses can therefore be designed to affect the ultrasonic rays in the same manner as they are used in light. These lenses can be used to focus the waves in liquids or in gases and may be formed of plastics, metals, or liquids.

**Loss of Energy in Ultrasonics.** The dissipation in an ultrasonic system is due primarily to the viscosity or damping of the medium. Besides this, heat conduction and radiation between the compression and rarefaction sections of the waves seem to have a major part in the losses experienced.

The greatest amount of energy is commonly produced in ultrasonics by these systems which are designed for agitation. One investigator[1] obtained about 300 watts in such a system, using transducers 60 to 70 cm across their faces. A number of investigators have reported obtaining 10 watts/sq cm.

Most ultrasonic energy measurements are made by noting the rise in temperature in the medium. This medium is usually an oil bath in which the transducer vibrates. In order to make such measurements reliable, both the frequency and the amplitude of vibration must be controlled carefully.

Small amounts of energy are sufficient for test and signal purposes. The amplitude in such cases can be crudely indicated by the amount of radio-frequency peak-to-peak voltage on the transducer (usually a crystal). A satisfactory pulse for testing materials and for some signaling would be a 1,000-volt peak of about 1- to 4-$\mu$sec duration.

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[1] Freundlich, H., K. Sollner, and F. Rogowski, Die Einwirkung von Ultraschallwellen auf Gele, *Kolloidchem. Beihefte*, **37**, 223 (1933).

**Experimental Measurements of Energy.** *The Balance Method.* By suspending a sensitive balance in the ultrasonic field it is possible to measure the power generated. If the source is below the balance pan, the pressure of the ultrasonic waves is indicated by the associated pointer in the same manner that weight is measured. One such system is shown in Fig. 1-15.

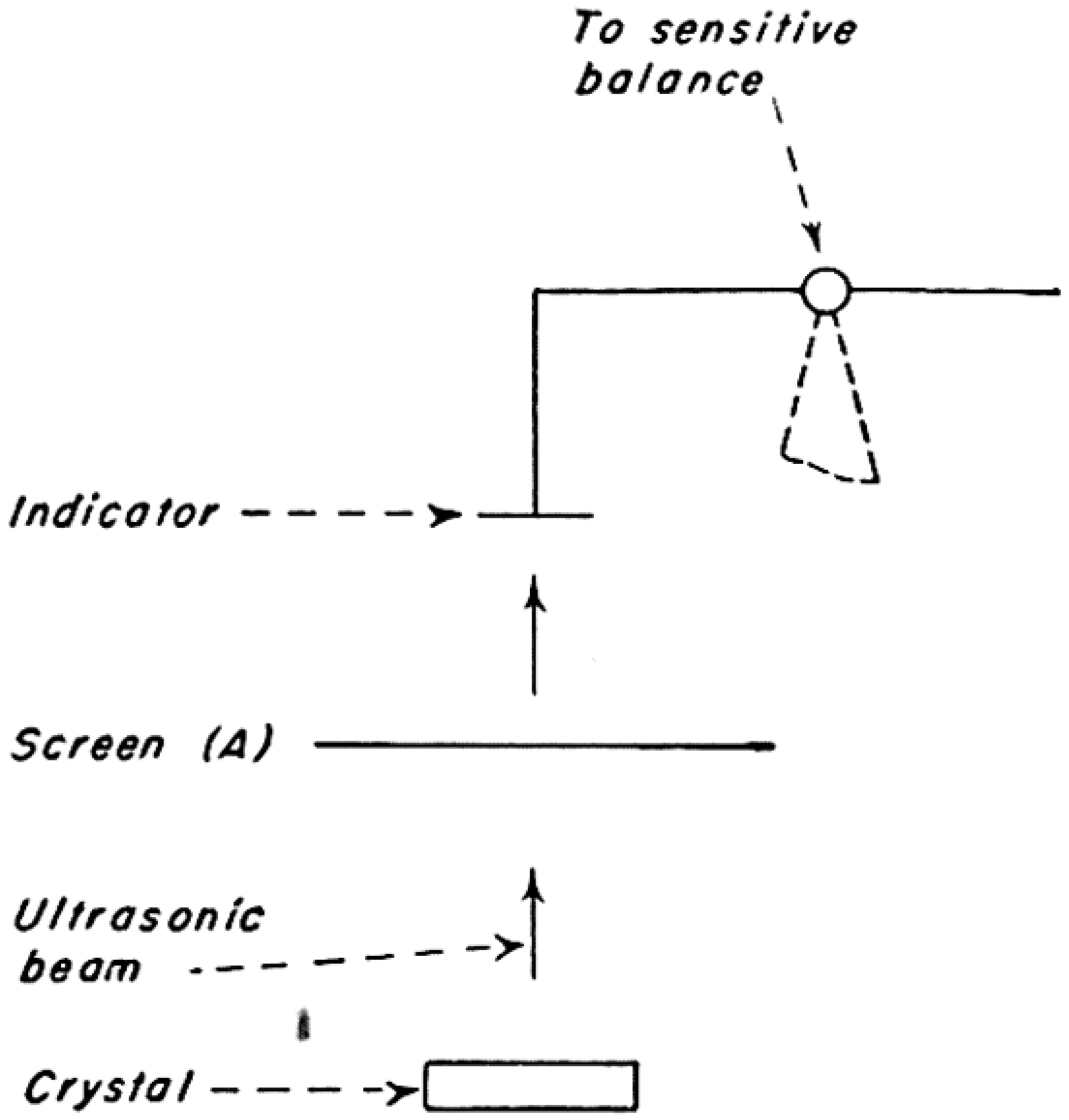

FIG. 1-15. Balance method of measuring energy.

Hydrodynamic flow of the liquid must not be allowed, since it produces extraneous variations in the readings. Screens of cellophane or similar material can be used. Such a screen is shown in the figure as *A*, where it allows the ultrasonic waves to pass freely but interrupts the formation of currents in the liquids.

In this system a quartz crystal is used as a transducer. The energy output at frequencies as great as 50 mc can be measured by such a method.

*The Echo Method.* The pulsed system also offers a method of measuring energy. A pulse of ultrasonics is sent through a given amount of liquid, and both the amplitude of the echoes and their number are noted. The echoes can be measured in any of the usual electronic manners, *i.e.*, by calibrating a cathode-ray tube or by other means. The comparative amplitude of the echo indicates the amount of energy.[1]

**Ultrasonic Signaling in the Ocean.** One of the chief applications of ultrasonic waves has been in submarine signaling, where they are widely used for the location of obstacles and of enemy ships. The pulse method is generally used, and the time between the sending and reception of the pulses is an indication of the position of the reflecting objects. However, a submarine signaling indicator commonly shows a series of reflections arriving at various times as well as the genuine signal, which is the important indication. These spurious indications may be reflections from the surfaces of the water, usually from the troughs of the waves.[2] Since very little absorption occurs during the transmission of ultrasonics in the sea, a great many such reflections are likely. Besides this, there is a certain amount of reflection from the bottom of the ocean, although this is not so troublesome as that from the top. Difficulty is also encountered with temperature gradients and with movement within the body of liquid.

**Ultrasonic Propagation in Air.** A great deal of work has been done in the field of ultrasonic transmission through the atmosphere, since this application offers a method of sound ranging, communication, altitude determination, etc. Generally, the order of frequency is from 10 to 30 kc, and it is necessary to propagate within 10 ft of the ground.[3] Many problems make this type of work very difficult, specifically the fact that there is considerable scattering by the lower atmosphere and also by different kinds of various natural obstructions. In addition to this the waves are affected by winds and air-temperature gradients that exist close to the earth. Rain also attenuates sound, and for all these reasons the sound energy is sharply reduced.

Compressed air whistles are often used for the production of the ultrasonic energy, and the receivers may be either resistance coupled or heterodyne. Parabolic reflectors can be used to concentrate and direct the energy.

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[1] G. E. Teeter, Jr., Absorption of Supersonic Waves in Liquids, *J. Acoust. Soc. Am.*, **18**, No. 2, October, 1946.

[2] Urick and Saxton, Surface Reflection of Short Supersonic Pulses in the Ocean, *J. Acoust. Soc. Am.*, **19**, No. 1, January, 1947.

[3] Schilling *et al.*, Ultrasonic Propagation in Open Air, *J. Acoust. Soc. Am.*, **19**, No. 1, January, 1947

Ultrasonic methods have not been so successful when used for this type of application as when used in the testing, seismic, and submarine signaling fields.

**Propagation through Wires.** Some work has been done in attempting to send ultrasonic vibrations through ordinary wires for signaling purposes. Low frequencies of the general order of 30 to 150 kc have been used. In order to couple the energy into the wire, one end is fastened to a crystal transducer for sending purposes and the other end fastened to a second transducer for receiving purposes. Such signaling has been done effectively over relatively short distances, but it has not been successful in long-distance communication. Bends and breaks in the wire will naturally interfere with the propagation of the waves and help dampen them quickly.

**Methods of Generating Ultrasonics.** There are a number of ways in which ultrasonics can be generated. The method chosen depends upon the power output necessary and the frequency range to be covered. Generators of the mechanical type such as tuning forks or Galton whistles can be used up to about 10,000 cycles. Power-driven whistles are capable of producing large amounts of energy. One special type of whistle sometimes used is the gas current generator. Another mechanical method of producing ultrasonic waves is the vibration of a rod of glass or metal.

With the possible exception of whistles and sirens, few of these mechanical methods are used in the generation of ultrasonics for practical purposes. The frequency range mechanically attainable is extremely limited, and all high-frequency ultrasonics are generated by other means.

Some ultrasonic generators use a spark gap or an arc of direct current to produce vibrations. Units such as these are based upon thermal principles and are not commonly used at present.

The most common and the simplest method of producing high-frequency ultrasonics is by the use of magnetostriction or crystal transducers. Magnetostriction is used when frequencies of the order of about 100,000 cycles are needed, while crystals are used for most frequencies above that and can be easily driven in the megacycle range to generate frequencies of as high as about 15 mc. Much higher frequencies can be obtained by vibrating the crystal at one of its harmonics.

These two latter methods of ultrasonic generation are the most widely used today, to the practical exclusion of all other methods.

**Detection of Ultrasonic Waves.** *Theory.* When ultrasonic waves are projected against a boundary, they exercise on it two different effects: One is the alternating pressure at the frequency of the wave propagation, and the other is a direct pressure due to the radiation.

The alternating pressure is determined by the formula

$$J = \frac{dc}{2}\left(\omega A^2\right) = \frac{Pu}{2}$$

where $J$ = intensity per centimeter squared in unit time
$d$ = density
$A$ = maximum amplitude of the vibration particles
$P$ = sound pressure
$u$ = velocity amplitude of the individual particle

A quartz crystal will actually respond to and follow these variations, but most mechanical systems, because of their inertia and mass, cannot vibrate at the frequency necessary to reproduce suitably such very rapid fluctuations. However, besides the high-frequency vibration there is also the unidirectional effect, which is expressed by the formula

$$S = \frac{1}{2}(K + 1)\frac{J}{c}$$

where $K$ is the ratio of the specific heats.

A measurement of the unidirectional pressure gives an indication of the intensity of the ultrasonic field and is the basis of much of the practical work done in such measurement except when crystals are used.

*Methods.* In the middle nineteenth century, Kundt described a means of making ultrasonic waves visible by powdering the object in which they are traveling with a very fine dust such as lycopodium. This dust arranged itself on the surface of the piece in a configuration that was determined by the dimensions and shape of the wave. Similar methods were also used in liquids, where a fine suspension of dust such as powdered coal or coke may be employed. Any form of mist, dust, or smoke or even small bubbles can be used to indicate the passage of ultrasonic waves in the various media. There has been a good deal of discussion of these means in the classic literature, but they are mainly interesting in a historical connotation or for laboratory use.

A method still used for experimental work is the measurement of ultrasonic pressure by means of a radiometer (Fig. 1-16), which is an apparatus that works on the principle of a torsion balance. It is so arranged that the ultrasonic energy impinges on a mica disk balanced by a weight. This disk is rotated by the unidirectional pressure. The pressure of the ultrasonics on its face depends on the amount of reflection from the disk, and it is therefore important that the disk reflect the total energy. Since the reflection between a solid and air is practically 100 per cent, most of these disks consist of two thin sheets of mica with an air space imprisoned between them. The pressure on the disk is then indicated by the amount of rotation, which can be calibrated in any convenient units.

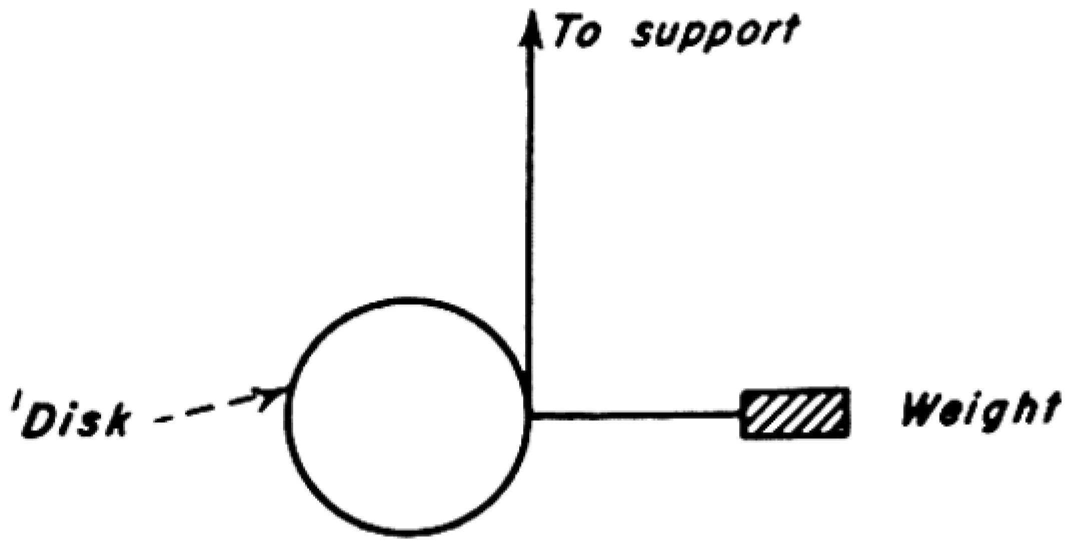

FIG. 1-16. Ultrasonic radiometer.

Those systems which have been described up to this point are mechanical ones, but there are also several thermal ones. If a wire is suspended in an ultrasonic field and heated, it will be affected by the field. Platinum wires forming one side of a Wheatstone bridge can be used. The resistance of the wire fluctuates directly with the amplitude of the ultrasonic waves.

This change usually takes the form of a drop in the resistance and is linear enough so that the ultrasonic amplitude can be directly calibrated with it.

A number of optical methods have been suggested in the past and have also been described in the literature. Most of these work on the following basis: A change in the index of refraction of a liquid or transparent solid takes place when ultrasonic waves pass through it. Generally the compression area appears as a dark line. With such systems it is ordinarily easier to investigate standing waves than traveling ones. However, both can be examined. Diffraction images can be obtained for any single frequency; and when the crystal vibrates in a number of different frequencies, the patterns for each of the frequencies will be indicated.

As in the case of transmission, the most satisfactory types of receiving systems are the ones based upon recent electrical developments and use as a transducer either a quartz crystal or a magnetostriction rod.

**Common Ultrasonic Definitions.** The *amplitude* of vibration is the distance that a particle is displaced during the passage of an ultrasonic wave.

*Wavelength* is the distance between two particles that are at the same point on the wave, *i.e.*, the distance between points of equal phase.

*Frequency* is the number of vibrations per second.

*Nodes* are points on the wave where there is no particle motion.

*Antinodes* are points where there is maximum particle motion.

*Continuous wave* is a wave that does not vary in any way during its transmission.

*Modulated wave* is a wave that has a continuously changing characteristic.

*Wave train* refers to a group of waves that are not followed or preceded by other waves. The individual waves may be identical or different.

*Attenuation* refers to the loss of energy during the passage of an ultrasonic wave.

*Transducer* is a unit for producing or receiving ultrasonic waves.

## CHAPTER II

## ULTRASONIC WAVES: FURTHER THEORY

There are a number of other characteristics of ultrasonic waves that are important in practical applications. Moreover, it may be advisable to consider some of those already mentioned in slightly more detail. However, the characteristics considered are exclusively those which have a specific relationship to ultrasonic engineering.

**Curves.** Ultrasonic waves can be represented graphically by displacement curves. These are graphs representing the form of the wave, in which the $X$ axis denotes the distance the wave has traveled along its path of propagation and the $Y$ axis the displacement of the particle from its original position. When the waves are shear, such a curve actually looks like a picture of the wave motion; when they are longitudinal, the displacement of the particle forward is usually represented above the $X$ axis and that backward, below it. Such curves are very useful in the consideration of wave motion.

Waves are sometimes referred to by the name of the curve that represents them, *i.e.*, sine wave, square wave, etc. This refers to descriptive characteristics of the wave only.

It should always be remembered that the graph merely describes the motion or displacement and is not an actual pictorial representation of the wave.

**The Wave: Simple Harmonic Motion.** The sine wave is usually considered the simplest and most basic type. It is also sometimes referred to as *simple harmonic motion* and is represented as the projection of a unit radius on a plane as the radius rotates about its center. The mathematical description of such an action can be written in the form

$$X = a \cos (\omega t - \phi)$$

This expression therefore represents a sine wave, and any ultrasonic wave in its simplest and purest form can be so represented, no matter what is the motion of its particles, *i.e.*, whether it is longitudinal or shear. The wave shape does not picture the actual displacements of the particle in the medium; it merely represents that action, and the representation of various waves may be identical, although the actual particle motion is not.

The time along a sine wave, *i.e.*, the time duration passed since the beginning of the action, is referred to as its *phase* and is expressed as an angle of rotation of the radius mentioned. Since the wave repeats every 360 deg, all multiples of 360 deg are subtracted and the phase angle is less than that amount.

The amplitude of a sine wave is the distance from peak to peak across its width. This represents the maximum displacement of a particle in the medium (see Fig. 2-1).

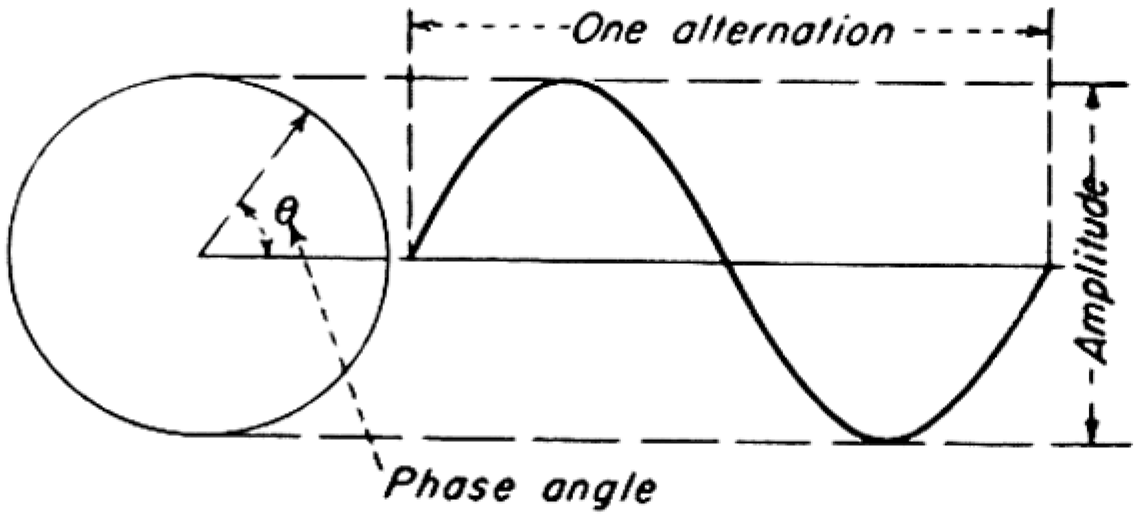

FIG. 2-1. Sine wave.

The period refers to the time necessary for one wave, *i.e.*, 360 deg, to take place, and the frequency gives the number of these waves or alternations taking place in unit time. The frequency is the reciprocal of the period.

Wave motion can, of course, be plotted or viewed by oscilloscopic means. The figure may be very complex, especially when the particles are being displaced at the same time by more than one wave, very often in different directions. Such a pictorialization is referred to as a *Lissajous figure* and shows the actual motion of the particle, no matter how many simultaneous forces are acting on it.

These conceptions are extensively considered in any text on wave motion. From a physical point of view, ultrasonic waves may be considered as being merely of a simple harmonic type, although in actual practice such a condition is only approximated.

The major concept is that of a constantly repeating particle motion being propagated through a medium.

Ultrasonic waves can be examined oscillographically by synchronizing them with the sweep, converting them to electrical energy, and causing them to repeat in such a way that each representation falls exactly on top of a prior one. This produces a single stationary pattern, which can then be viewed at leisure.

**Complex Waves.** In actual practice waves may occur in any shape whatever, either regular and symmetrical or not. Frequently the investigator will be confronted by a pattern that appears to have no particular configuration. On the other hand, more often the wave may be conveniently classified in some way, *i.e.*, square (when it is more square than otherwise) or triangular (more nearly triangular than any other shape), etc. Waves rarely follow a configuration closely; they merely approximate it.

**Fourier Analysis.** Fourier's theorem stated in the simplest form that any complex wave, such as a square pulse or other irregularly shaped function, could be analyzed and shown to contain or be made up of a number of simple harmonic waves of various frequencies and amplitudes. Actually each complex wave would contain an infinite number of such sine waves.

The theorem is usually stated as

$$x = a_0 + a_1 \cos \omega t + a_2 \cos 2\omega t + \cdots + b_1 \sin \omega t \\ + b_2 \sin 2\omega t + \cdots +$$

The statement is extremely important in that it offers a method of analyzing (and also of conceiving the action of) irregular waves.

An approximation of the shape of the irregular wave in question can be made by taking the first three or four components of a complete Fourier analysis, which, as stated, contains an infinite number of terms. However, the greater the number of terms taken the more closely will the result approximate the original function.

Analysis of complex waves can be carried out in practice either graphically or by means of one of the commercial instruments available for that purpose.

Fourier analysis of short pulses of oscillation, such as those used in pulsed systems, is extremely complex, and such waves contain a very wide range of harmonics.

Theoretical analysis is rarely carried out in the field, but the physical concept of the presence of these many components is valuable in understanding the action of ultrasonic waves.

Any wave that can be produced is a complex one; *i.e.*, there is no such thing as a pure sine wave in practice, either because of the discontinuities at the beginning or end of the transmission or because of an irregularity in the generator itself. Mechanical elements such as crystals generally cannot produce waves of such great purity as electrical ones. This is obvious when the method of support and excitation is considered.

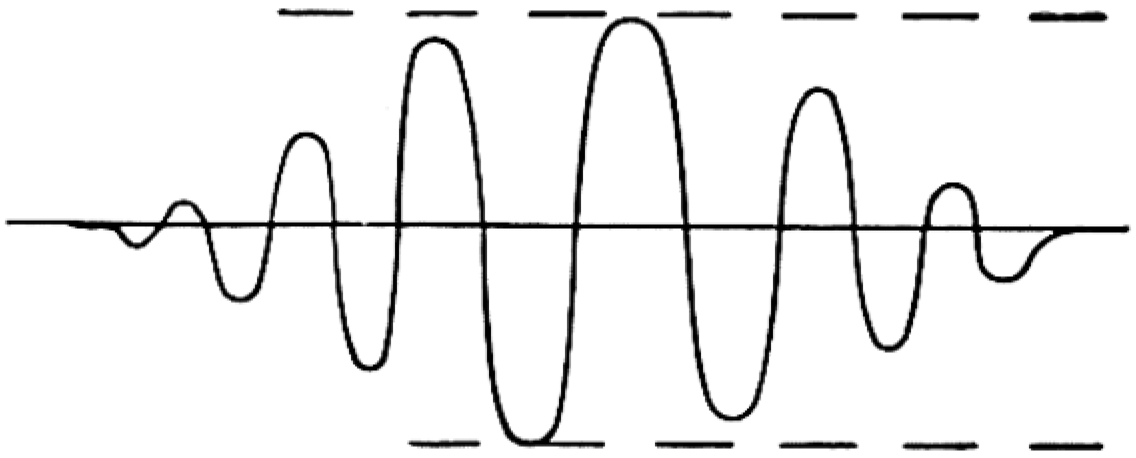

FIG. 2-2. Wave train.

All ultrasonic waves are therefore subject to Fourier analysis, especially in the cases of pulsed or modulated energy, which are especially rich in harmonics. This is important because it means that higher orders of the original frequencies can be received or indicated. Thus the analysis of waves both before and after transmission may give information on the material through which the waves travel.

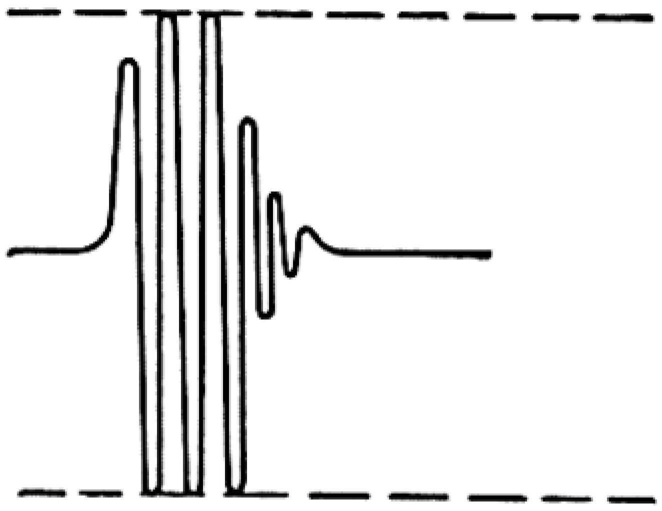

FIG. 2-3. Typical pulse shape.

**Wave Train.** A wave train refers to a short group of waves before or after which there are no waves (Fig. 2-2). Such a group is usually called a *pulse* and may be of several different shapes. For one thing, the individual waves in such a pulse may be of about the same amplitude, and it may stop and start very rapidly, so that its envelope, *i.e.*, the locus of points on its extremes, is essentially a square wave (Fig. 2-3). The pulse may also be such that it both builds up and decays gradually, in which case that locus will look like a half cycle of a sine wave. The pulse may also build up rapidly and decay exponentially (Fig. 2-4), in which case it is called a *decayed* or *damped train* and takes the form familiar in exponential damping. This last case is the most common.

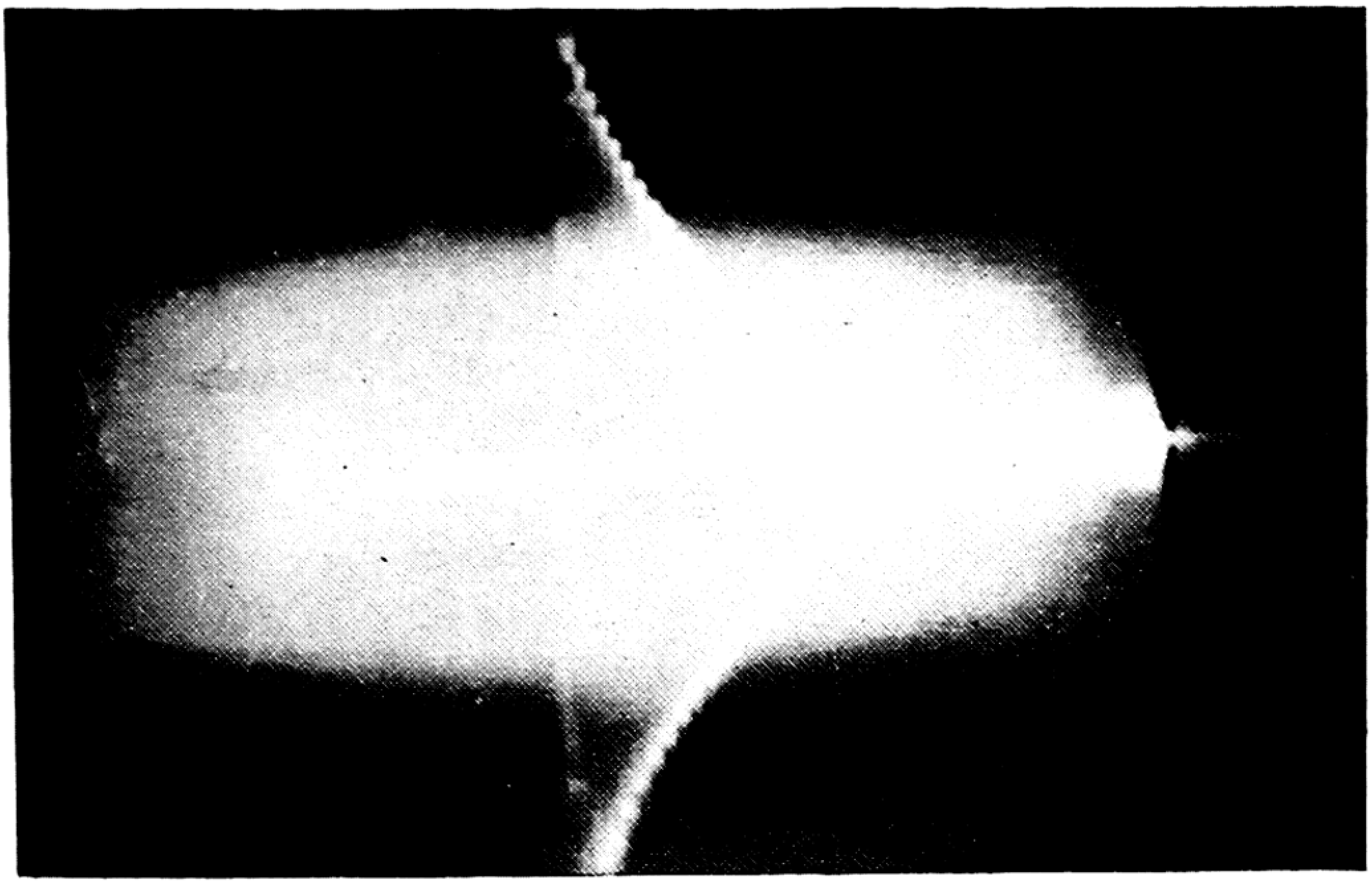

FIG. 2-4. Damped wave train.

All these types of wave trains are used extensively. All are rich in harmonics, and analysis of a wave train by Fourier or other methods will therefore show a great number of frequency components.

**Theoretical Discussion of Types of Ultrasonic Waves and Their Velocities.** As already mentioned, several types of ultrasonic waves can exist. Such waves are the $L$, $S$, and surface wave briefly described heretofore.

The theoretical discussion of these types of motion is important, since it correlates the several fields (sound, vibration, ultrasonics, etc.) of which ultrasonics is a part and gives a more specific view of what is occurring. The treatment is necessarily very brief and discursive.

These waves may occur in any of the forms of modulation already mentioned. *The type of ultrasonic wave refers only to the particle motion, not in any way to the wave shape.*

*Theory.* A particle in any material can obviously experience three distinct displacements: one in the $x$ direction (usually called $u$), one in the $y$ direction (called $v$), and one in the $z$ direction (called $w$). Any particle motion can therefore be resolved into a combination of three displacements.

From any text on elasticity[1,2], equations describing the motion of these particles are given as

$$(\lambda + G)\frac{\partial e}{\partial x} + G\nabla^2 u - \rho\frac{\partial^2 u}{\partial t^2} = 0$$

$$(\lambda + G)\frac{\partial e}{\partial y} + G\nabla^2 v - \rho\frac{\partial^2 v}{\partial t^2} = 0$$

$$(\lambda + G)\frac{\partial e}{\partial z} + G\nabla^2 \omega - \rho\frac{\partial^2 \omega}{\partial t^2} = 0$$

where $\lambda$ = Lamé's constant
$G$ = modulus of rigidity (shear modulus)
$e$ = volume expansion
$\nabla^2$ = Laplacian operator

These are equations of motion and represent types of displacement in which the body in question remains continuous, *i.e.*, in one piece, in equilibrium, so that it does not move as a whole, and obeys Hooke's law that the strain is proportional to the stress. They also represent the motion of the body about a static state in which the forces acting are due only to the internal stresses and shears and to the particle acceleration forces. From these equations, all types of ultrasonic wave motion can be derived.

The above equations completely describe all the possible types of motion of a particle, subject to the given boundary conditions. Physically, however, experimental conditions may not allow the realization of all these motions. The equations to follow are derived from these and represent typical periodic wave motions. The equations represent the theoretical case and may be difficult to apply directly. They therefore act more as a guide to the experimenter than as an actual explanation of a phenomenon.

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[1] Timoshenko, "Theory of Elasticity," McGraw-Hill, 1936.

[2] Rayleigh, "Theory of Sound," Macmillan, 1877.

**Longitudinal Waves.** The longitudinal waves common to ultrasonics are defined as those in which the particle velocity is restrained to a motion in the direction of the wave propagation. They are dilatational and irrotational; *i.e.*, there is a change in the body volume; and to state it crudely, particle motion consists of strain without rotation.

The equations for such waves in the $x$ direction reduce to

$$(\lambda + 2G)\frac{\partial^2 u}{\partial x^2} = \rho \frac{\partial^2 u}{\partial t^2}$$

Physically, this equation states that the particle displacement is a function of $x$ and a function of $t$. In other words, if it were plotted as a function of $x$ for a constant value of $t$, the shape of the displacement will be proportional to the plot of $u$ as a function of time. The proportion is that of $\lambda + 2G : \rho$.

The terms $\lambda$ and $G$ are elastic constants; *i.e.*, they are determined by the characteristics of the material; and $\rho$ is the mass density, *i.e.*, the mass per unit volume. These characteristics are physical entities that can be measured in a material.

Essentially, this equation states that the only possible particle velocity is in the $x$ direction. This is the ideal condition in the propagation of $L$ waves. However, in actuality, although the greatest motion is in this direction, there is always some shear stress, since the edges of the path cannot move back and forth quickly.

**Shear Waves.** Shear waves have been defined as those whose particle motion is perpendicular to the direction of wave travel. In such a case when the volume expansion $e$ is zero, the equation is

$$G\left(\frac{\partial^2 u}{\partial y^2}\right) = \rho\left(\frac{\partial^2 u}{\partial t^2}\right)$$

This is known as a *wave of distortion.* In other words, the volume of the entire body does not change, although its boundaries may. (It may be noticed that the condition of no volume change is set by definition.)

Considering this case physically, it may also be noted that the displacement at a particular point in space corresponds exactly to the displacement at a particular different point in time over the entire wave, with the scale factor $\sqrt{G/\rho}$. This means that a particle will occupy a particular point in space at periodic intervals of time.

**Rayleigh or Surface Waves.** These are waves which travel over the surface of the part without any essential penetration into it. Lord Rayleigh based his description of these waves on two assumptions:

1. There is a combination of two waves existing on the surface: one distortional and the other dilatational.
2. Both types exist on the surface only.

When the conditions above are solved for, the wave velocity depends on $\mu$, since both $\lambda$ and $G$ are functions of $\mu$ and they in turn control the velocities of the two types of waves. The quantity $\mu$ represents the displacement normal to the pressure. The velocity of a surface wave can be solved for when the physical characteristics are known.

Many interesting phenomena may be associated with real or spurious surface waves. In ultrasonic work it is very often difficult to separate out various types of waves, since many forms of receivers and indicators cannot distinguish, for example, longitudinal from shear waves. They merely indicate the presence of a wave, which may be of any type. In working with large masses of metal, reflections will occur, which the passage of the hand or some other damping medium over the surface will cause to be damped out at certain points. This would, of course, occur in the case of any type of wave if it were hitting the surfaces at that point. However, in certain cases reflections may be observed that seem to return from the edge of a large object, and the time elapsed between the sending of the pulse and this reflection seems to coincide with what would be expected of surface waves.

This is particularly interesting in that the Rayleigh conception of such a wave would appear to be a mathematical fact, but not necessarily an easily produced physical one. The waves do not necessarily exist in exactly the same form as described. In an experimental sense, most waves exist within a medium; they do not exist only on a surface.

If a thin film of oil or similar material is spread over such a surface, waves may travel in the oil and reflections will occur even when the film is only a few molecules thick. Exactly what type of wave exists in such a case is questionable. Although the wave obviously travels within a fraction of a wavelength of the surface, it would not necessarily be a surface wave even though it is described as a wave traveling within a wavelength of the surface.

These waves may be theoretically obscure, but in practice they often cause definite spurious effects, and care must be taken that the surface of parts will not transmit waves at the same time that other types of ultrasonic work is being carried out and waves are being sent through the bodies themselves.

**Angular Transmission.** The transmission of ultrasonic energy into a medium at an angle other than the normal is of particular importance,[1] and the theory will therefore be briefly considered. This type of transmission has been widely discussed in connection with earthquakes, and any good text on seismology is of interest in connection with it.

When energy is transmitted into a medium at an angle to its face, it must always be first transmitted through a coupling medium. Placing, for example, a piece of the same material to act as the coupling between the crystal and the medium does not meet this requirement, and transmission is then considered to be at right angles to the front surface.

The material that forms the angle may be gas, liquid, or solid as long as the medium into which the energy passes is different. However, in ultrasonic work transmission from a gas to a solid or vice versa has never been carried out successfully enough to merit special consideration. The other two cases are of great importance in all phases of ultrasonics and seismology.

From what has already been said, it may be readily seen that angular transmission assumes refraction of the wave at the interface between the two separate media.

The transformation of types of waves makes angular transmission more complicated than it would otherwise be. However, even in those cases where the beams are not transmitted at an angle, internal reflections or beam spread may cause part of the energy to hit a surface at a glancing incidence. Such an occurrence will bring about a transformation of the wave in the usual manner. A more detailed consideration of this transformation is therefore advisable.

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[1] B. Carlin, Testing Welds with Supersonic Waves, *J. Am. Welding Soc.*, **27**, No. 6 (June, 1948).

**The Law of Angular Transmission.** The basic formula for the transmission at angular incidence is known as *Snell's law* and states

$$\frac{\sin\theta_L}{c_L} = \frac{\sin\theta_L'}{c_L'} = \frac{\sin\theta_S'}{c_S'}$$

where $\theta_L$ = angle of incidence of the longitudinal waves in one medium
$\theta_L'$ = angle of transmission of $L$ waves in a second medium
$\theta_S'$ = angle of transmission of $S$ waves in a second medium
$c_L$ = velocity of $L$ waves in the first medium
$c_L'$ = velocity of $L$ waves in the second medium
$c_S'$ = velocity of $S$ waves in the second medium

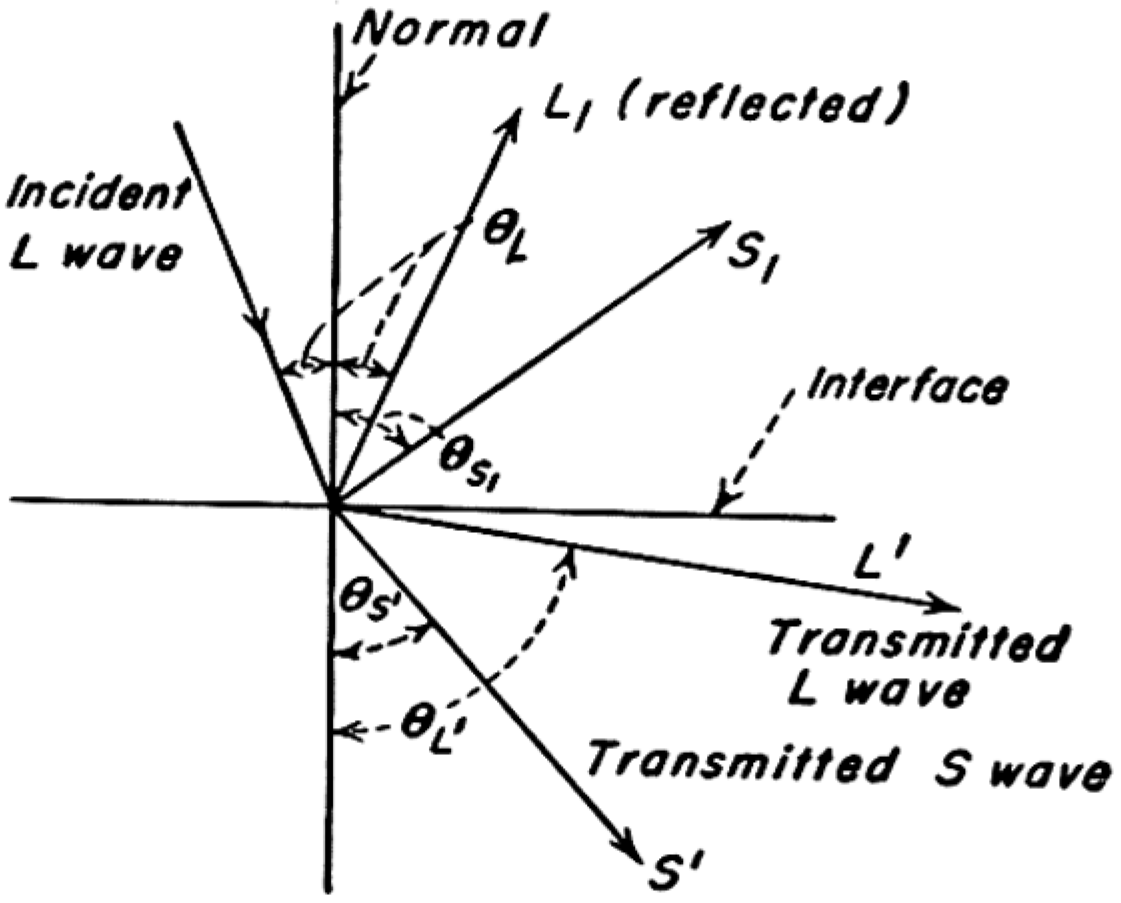

FIG. 2-5. Waves produced at a boundary by an incident $L$ wave.

**Wave Transformations at Angular Incidence.** In the case of an $L$ wave, which is to be transmitted ultrasonically, it can be seen from Fig. 2-5 that when this wave is incident upon an interface between two materials at certain angles, four resultant waves may appear, of which two are transmitted. One of these two in each case is an $L$ wave, and the other an $S$ wave. All these waves may not exist in practice, but they are theoretically possible in certain cases.

The complete action is as follows: When an $L$ wave is incident in the normal direction, it is transmitted through as 100 per cent $L$ wave. As the angle is rotated from 90 deg, a point comes that is known as the *first critical angle.* Between 90 deg and this first critical angle the $L$ wave is transmitted into both $L$ and $S$ waves of various percentages. As the angle continues to rotate, a second point is reached, which is known as the *second critical angle.* In that portion of the rotation between the first and second critical angle only $S$ waves are produced. For those points between the second critical angle and grazing incidence no waves enter the material. Therefore, by choosing the angle of incidence it is possible to choose one of a number of conditions. They are

1. Both $S$ and $L$ waves are produced at the surface, the angle of refraction of the $L$ wave being greater than that of the $S$ wave in every case.
2. Between the critical angles only $S$ waves are produced, and the angle of refraction of the $L$ wave is sufficiently great so that the $L$ wave exists only theoretically and is outside the boundaries of the material.
3. All angles of refraction are so great that there are essentially no waves entering the material.

The case of $L$ waves incident on the material is the more important one, since shear waves cannot be transmitted through liquid and are therefore rarely used in ultrasonic work. Moreover, it is difficult to couple shear waves into a solid, since a stiff couplant is necessary.

To recapitulate, the critical angles are those angles bounding the regions where only one type of wave, the $S$ type, exists. The first critical angle (see Fig. 2-6) exists where the transmitted $L$ waves graze the interface; *i.e.*, $\theta_L' = 90$ deg. Between this angle and the second critical angle all the energy is in the form of a transmitted $S$ wave. The $L$ wave no longer exists.

The second critical angle is the one where the $S$ wave first grazes the surface; *i.e.*, $\theta_S' = 90$ deg. Beyond this point there is a total reflection, and no energy is transmitted through the interface.

The critical angles can be calculated from the formula if the velocities are known. The sine of 90 deg, *i.e.*, 1, is then substituted for one sine, and the equation solved for the other. Both critical angles are found in this manner.

In a like manner, the equation can be solved for any angle of transmitted *S* wave or *L* wave, for a given angle of incident *L* wave (as long as both exist).

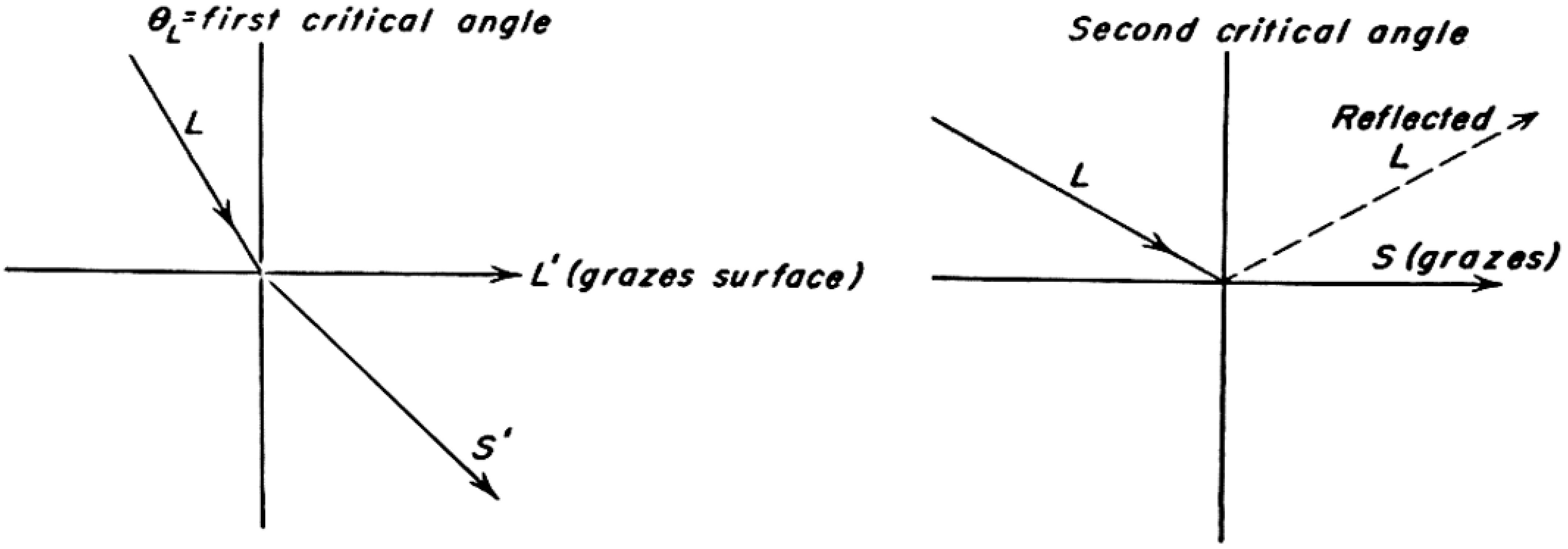

FIG. 2-6. Critical angles.

These conditions may exist between two solids when the velocities of various types of wave are defined as in the following paragraphs and as shown in Fig. 2-7. In the case of most liquids incident on solids this is true, and it also may be true with many solids on solids. It is rarely true with solids incident on a liquid. The transformations do not occur to any extent between a solid or liquid and a gas because of the very great reflection at an interface.

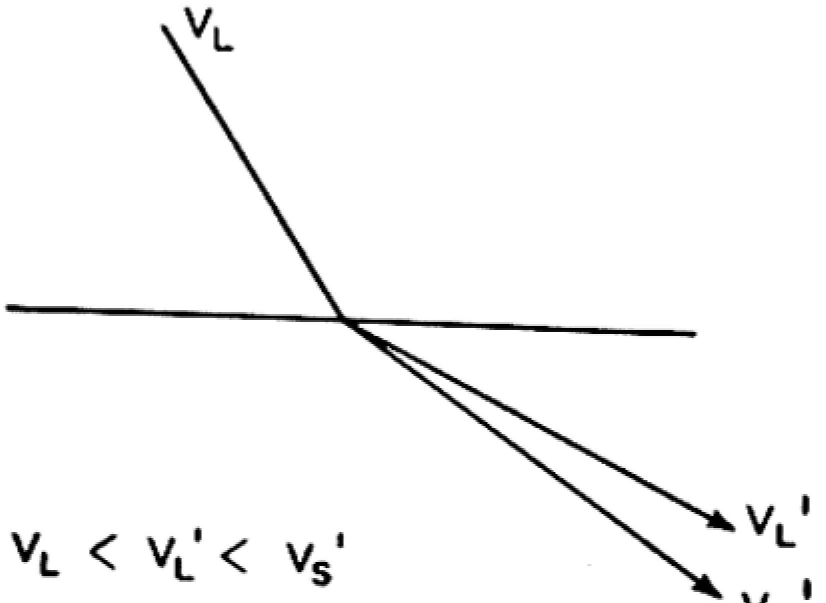

FIG. 2-7. Conditions for wave transformation.

Equations can therefore be set up for these cases and are valuable in determining what happens to the wave types during transmission at angular incidence. Critical angles normally run from about 20 to 60 deg with solid materials incident on other solids.

In choosing two materials it is possible to choose such angles that they will follow the laws of refraction already specified, *viz.*, having two critical angles between which all *L* waves are transposed into *S* waves, if the velocities of the media are defined by the following relation. If the velocity of the entering *L* wave is taken as $V_L$, the velocity of the refracted $L$ wave as $V_L'$, and the velocity of the refracted $S$ wave as $V_S'$, then the condition for the production of total $S$ waves from an incident $L$ wave will be specified only when $V_L$ is greater than $V_L'$, which is in turn greater than $V_S'$.

**Between Two Solids.** In the case of an incident $L$ wave on an interface Knott's equations give

$$S_1 + a\,(L - L_1) = S' + a'L'$$

$$bS_1 + (L + L_1) = -b^2S' + L'$$

$$-\,2bS_1 + (b^2 - 1)\,(L + L_1) = 2\,\frac{G'}{G}\,b'S' + \frac{G'}{G}\,(b'^2 - 1)\,L'$$

$$(b^2 - 1)\,S_1 - 2a\,(L - L_1) = \frac{G'}{G}\,(b'^2 - 1) - 2\,\frac{G'}{G}\,a'L'$$

These four equations with four unknowns give the properties of the waves.

The power equation is

$$adL^2 = adL_1^2 + bdS_1^2 + a'd'L'^2 + b'd'S'^2$$

where $L$ = amplitude of the incident $L$ wave
$L_1$ = amplitude of the reflected $L$ wave
$S_1$ = amplitude of the reflected $S$ wave
$S'$ = amplitude of the transmitted $L$ wave
$L'$ = amplitude of the transmitted $S$ wave
$G$ and $G'$ = coefficients of rigidity
$a = \cos\theta_L$
$b = \cot\theta_S$
$a' = \cot\theta_L'$
$b' = \cot\theta_S'$
$d$ = density

In other words, the incident power equals the sum of the resulting powers. There will be two critical angles in such cases (as defined before).

From these equations the power at an angle can be computed for any type of wave.

**Liquids to Solids.** The second most important case is that of transmission of waves from a liquid to a solid. Such a case is extremely significant in seismic work (earthquakes) and also in constructing ultrasonic transducers in which a body of liquid is trapped between the crystal and the work. Only $L$ waves exist in the liquid, and both $L$ and $S$ in the solid. The sine law as already stated is, of course, still effective.

Knott's equations for this situation are

$$S' = \frac{2a}{b'^2 - 1} L'$$

$$L - L_1 = \frac{a'}{a} \frac{b'^2 + 1}{b'^2 - 1} L'$$

$$L + L_1 = \frac{d'}{d} \left( \frac{4a'b'}{b'^4 - 1} + \frac{b'^2 - 1}{b'^2 + 1} \right) L'$$

The power is $adL^2 = adL_1^2 + a'd'L'^2 + b'd'S'^2$. In other words, the incident power must equal the sum of the powers in the resulting waves.

**Solids to Liquids.** In this case, the equations are as follows:

$$S + S_1 = \frac{2a'}{b^2 + 1} L'$$

$$S - S_1 = \left( \frac{1 - b^2}{2b} \frac{a'}{a} \frac{1 - b^2}{1 + b^2} + \frac{d'}{d} \frac{1 + b^2}{2b} \right) L'$$

$$L_1 = \frac{1 - b^2}{1 + b^2} \frac{a}{a'} L'$$

The power equation is

$$bdS^2 = bdS_1^2 + adL_1^2 + a'd'L'^2$$

There will be two critical angles as usual in most cases.

**Solids to Gas (Free Surface).** Knott's equations are (for $L$ waves)

$$L + L_1 = \frac{2b}{b^2 - 1} S_1$$

$$L - L_1 = \frac{b^2 - 1}{2a} S_1$$

Power is

$$adL^2 = adL_1^2 + bdS_1^2$$

(for $S$ waves)

$$\frac{L_1}{S} = \frac{4b\ (b^2 - 1)}{2ab + (b^2 - 1)^2}$$

The direction of travel of any wave and the amount of power it contains can be calculated for any angle of transmission from the formulas given. In some cases waves may be imaginary and therefore cannot actually be measured experimentally. However, the experimental measurement of other types of waves existing at the same time will show excellent agreement with the theoretical results.

**The Diffraction of Light.** The original application of ultrasonics to the diffraction of light in the testing of materials seems to have been made by Sokolov.[1] In his apparatus diffraction patterns were used as an indication of the presence or absence of ultrasonic energy.

The actual phenomenon was first noted by Debye-Sears[2] and is therefore usually referred to as the *Debye-Sears ultrasonic diffraction action.* The action makes possible the production of actual diffraction gratings and was concurrently demonstrated by Lucas and Biquard. The original theory was due to Brillouin.

The phenomenon depends upon the fact that the ultrasonic waves actually consist of alternating compressions and expansions, which alter the density of the medium through which they pass. The index of refraction depends on the density, and changes in the index cause the light to be diffracted. The central image and the various lines are separated from each other by a distance that depends on the frequency; and as the frequency becomes greater, this distance increases. Many different frequencies can be impressed on the system at the same time, and each will produce its own diffraction lines. The lines can therefore be used as an actual indication of frequency and also of velocity and wavelength.

[1] S. J. Sokolov, Practical Applications of the Diffraction of Light on Supersonic Waves, *Physik. Z.*, **36**, 142-144 (1935).

[2] P. Debye and F. W. Sears, Scattering of Light by Supersonic Waves, *Proc. Natl. Acad. Sci. U.S.*, **18**, 410 (1932).

This field of investigation has been widely examined, and exhaustive surveys of the work have already been published.[1] The application is extremely useful in tracing the passage of ultrasonic waves and in examining the action of lenses, crystals, etc.

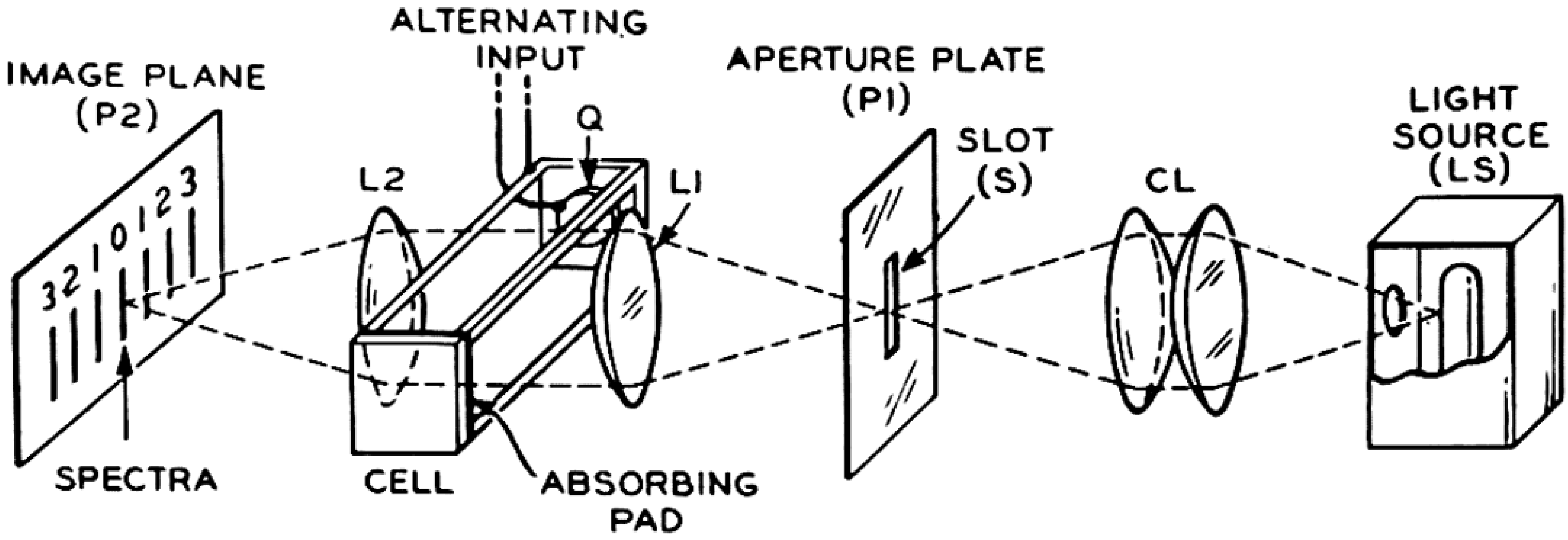

FIG. 2-8. Ultrasonic light diffraction system.

*Diffraction: Systems.* The action of a typical light diffraction system is shown in Fig. 2-8.[2] Light from a lamp is focused on a narrow slit. It passes through the slit, then through another lens, which again makes it parallel. The light is then sent through an ultrasonic cell, which consists of a quartz crystal transmitting through a liquid. An absorbing medium is usually placed at the other end of the beam so that there are no reflections. When ultrasonic waves are generated in this cell, the compression and rarefaction sections cause the light to produce a diffraction pattern. The system works on the general principle of the optical grating.

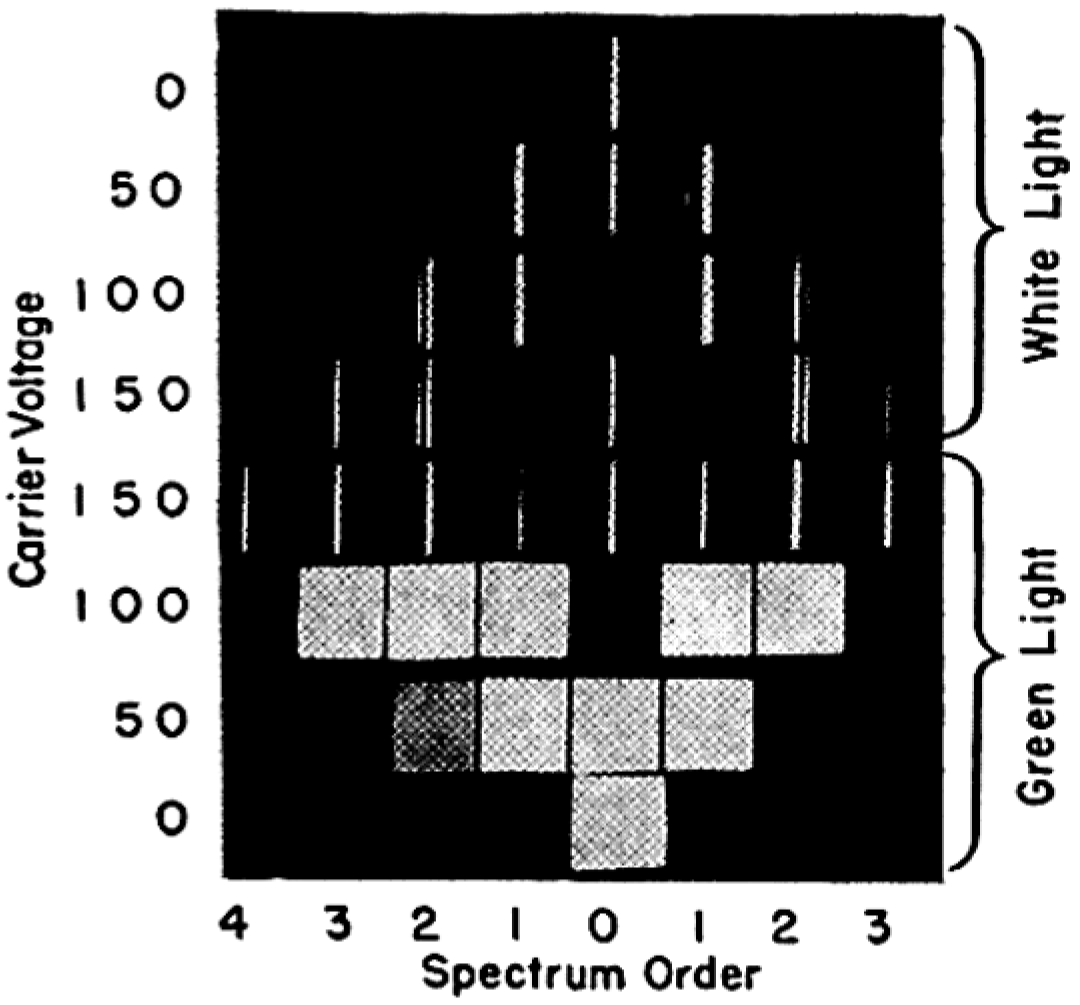

FIG. 2-9. Ultrasonic grating pattern.

Patterns from optical cells appear very similar to those produced by gratings. One such pattern is shown in Fig. 2-9.[3] As the ultrasonic beam becomes narrower, the pattern becomes sharper.

[1] Bergmann, "Der Ultraschall," Berlin, 1942.

[2] G. W. Willard, Ultra Sound Waves Made Visible, *Bell Lab. Record,* **25,** No. 5, 1947.

[3] *Ibid.*

If one frequency of vibration is sent through the liquid, one pattern results; if another is sent, a second pattern appears; if both frequencies are sent, both patterns appear as a combination of the two original patterns.

Since standing or stationary waves are due to two waves, one transmitted and one received, such a wave should produce a pattern similar to the superposition of those separately produced by each wave. Several investigators have shown that such is actually the case. When the waves are not stationary, but traveling, the Doppler effect can be shown experimentally.

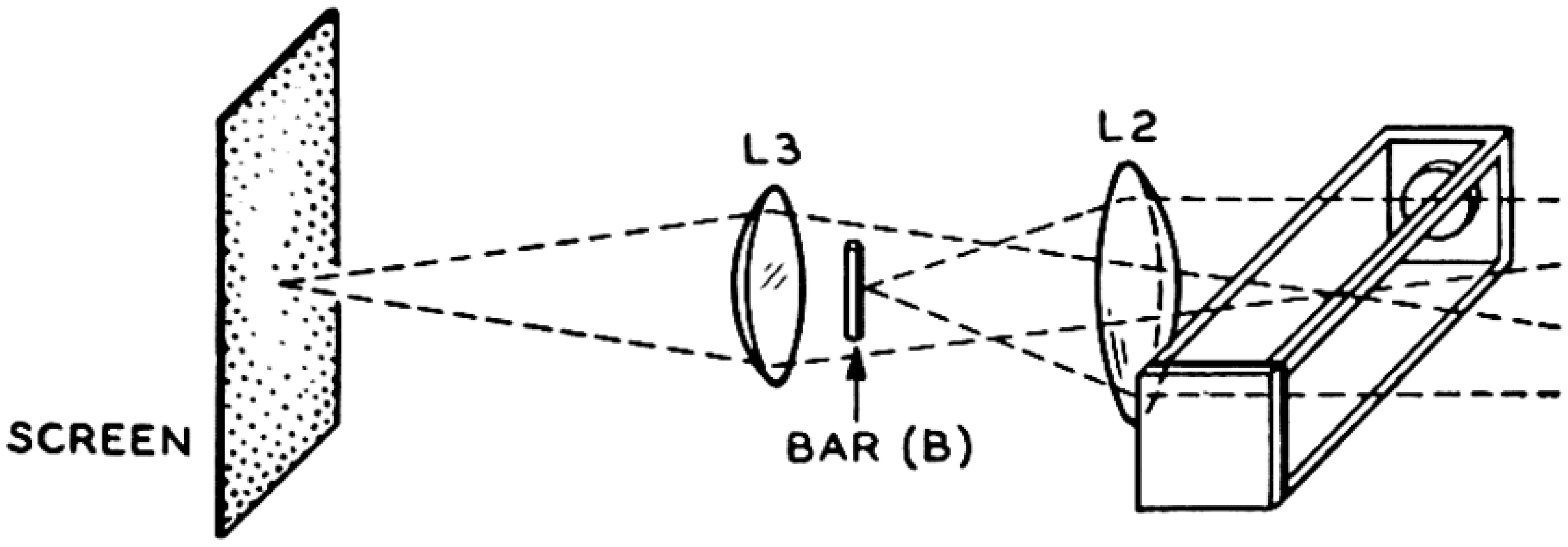

FIG. 2-10. Image system.

The theoretical explanation of diffraction is extremely complicated, and a satisfactory one is still not available.

It is further possible to make the entire shape and path of the ultrasonic beam visible by a change in the apparatus (Fig. 2-10).[1] This is accomplished by so placing an opaque bar that it blocks out the zero-order light produced by the ultrasonic beam. This has the effect of causing the amount of light transmitted to vary with voltage. Adding a lens after the bar focuses an actual picture of the beam on the screen.

Another method due to Bar and Meyer produces a similar picture by means of a screen full of small holes positioned before the ultrasonic cell. This apparatus produces a picture that looks as if it were made up of a large number of small dots. However, the unit has been successfully applied several times in obtaining pictures of ultrasonic waves.

The pictures of ultrasonic action obtained optically are extremely interesting and useful in making visible the passage of ultrasonic waves in a liquid or transparent solid. All kinds of phenomena such as focusing, diffraction, and reflection can be examined. In many cases there is no other way to get this information.

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[1] *Ibid.*

The actual shadow picture of a part can be made visible by passing an ultrasonic wave through such a part and projecting the transmitted portion of the beam onto a screen. The piece is usually immersed in a liquid bath, which acts to couple the ultrasonic energy in it. That part of the beam which has been interrupted by flaws in the material will be blocked out. Unfortunately, other characteristics of a material may also interrupt such beams.

In order to make the images more brilliant, experiments have been carried out with various types of particles that are suspended in the liquid and orient themselves in the beam,[1] arranging themselves according to the amount of ultrasonic energy that passes through the object under test.

The action of ultrasonics on light has also been suggested as a source of light for observing other rapidly recurring phenomena. This ultrasonic effect causes the light passing through the cell to become stroboscopic. A number of papers on the phenomenon have been published in Germany.[2] Generally, an elaborate optical system is used to isolate suitable orders of the diffraction pattern so that they can be used to view a rapidly repeating action stroboscopically. Since the systems are not widely used except in very theoretical work, they will not be further considered.

The diffraction of light has been extensively examined in specific applications in the literature by many investigators. Up to the present it has not been widely applied to any but laboratory uses in this country, but elsewhere it has been used as the basis for television and testing systems.

**Striation.** Another optical method of making ultrasonic waves visible is referred to as *striation* and is due to A. Toepler.[3] The optical system necessary is somewhat different from the diffraction type and is illustrated in Fig. 2-11. The arrangement shown is for making stationary waves visible. The parts under compression appear as dark lines, and the others as light ones. Different variations are possible but are not too important, since the diffraction method is the more widely used at the present time.

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[1] E. Czerlinsky, Non-destructive Material Testing by Supersonic Methods, *Jahrb. L.F.F.*, **1,** 723 (1942).

[2] P. Cermak and H. Schoeneck, *Ann. phys.*, **26,** 465 (1936).

[3] A. Toepler, *Ostwalds Klassiker,* 158.

The system operates on the principle that the refraction between compression and rarefactions bends the light away from a blocking screen. The same system can be applied to traveling waves if stroboscopic or very short pulses of illumination are used. A number of investigators have examined waves by such means.

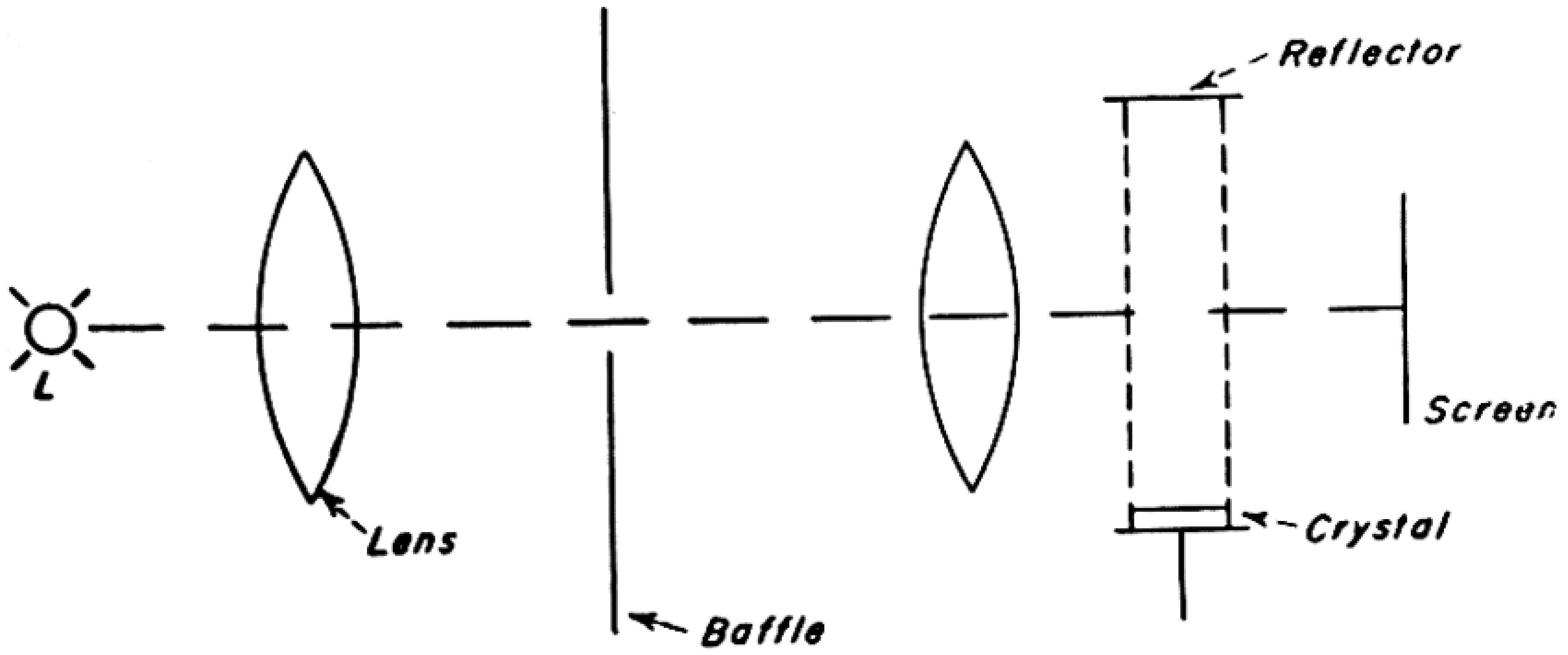

FIG. 2-11. Striation system.

**Transmission through Thin Plates.** In the case of ultrasonic waves traveling through a thin plate, Lord Rayleigh showed that the plate might be either transparent or not to the passage of the waves, depending upon its dimensions and physical properties. Such a situation is significant in ultrasonics, since there are certain thicknesses of materials (in the case of thin parts) that cannot be penetrated by the waves. This action was experimentally verified by Boyle and Lehmann.[1]

The case will be considered only where the waves are perpendicular to the part. Work was also done by Shraiber[2] on this problem. It was shown that transmission was greatest when the part thickness was a whole number of half wavelengths (or a suitable number of quarter ones).

When a thin sheet whose thickness is gradually changing is ultrasonically scanned, certain regions may appear to be opaque, which may be due to defects in the material or to the phenomena described.

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[1] R. W. Boyle and J. F. Lehmann, *Trans. Roy. Soc. Canada*, **21**, 115 (1927).

[2] D. S. Shraiber, Testing of Metals by the Use of Ultrasonics, *Z. Lab.*, **9**, 1001 (1940).

The part is impenetrable when

$$\frac{t}{(2n - 1)} = \frac{c}{4f}$$

where $f$ = frequency
$c$ = velocity
$t$ = thickness of plate
$n$ = integer

since

$$\frac{c}{f} = \lambda, \qquad t = \frac{\lambda(2n - 1)}{4}$$

The amount of variation of frequency to get a maximum transmission is

$$\frac{f}{f_1} = \frac{2n}{2n - t}$$

where $f$ is the original frequency and $f_1$, the one to which the change is being made. Shraiber decided that a frequency variation of 7 per cent would cause a sheet to be always penetrable.

This reasoning is partly responsible for the use of variable-frequency ultrasonic generators in the through type of material testing. The frequency of generation is varied over the above range. The same effect can be accomplished by the transmission of several frequencies concurrently.

It is sometimes important to design plates for minimum or maximum transmission. For example, backing plates of suitable dimensions may be designed to reduce back radiation to a negligible amount.[1] This can be done by using a plate of metal of about a half wavelength.

The calculations are based on the assumption that all the standing waves exist only within the plate and that the transducers are coupled directly to it. Methods for accomplishing such variations in frequency over a given range are simple and well known and will be discussed under continuous ultrasonic systems.

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[1] W. P. Mason, U.S. Patent 2,415,832.

Other applications are numerous, and the case is very important in designing efficient reflecting and transmitting plates.

**Absorption.** *Theoretical Considerations.* There have been a number of investigations of the amount of absorption in various solids, liquids, and gases. The results have not been uniform, and in most cases the theoretical and practical results have not agreed.

Most of the later investigations made in the field of absorption depend upon the measurement of sound radiation pressure at various points along the ultrasonic path. These measurements are carried out by using a torsion balance, which twists a given amount for a certain degree of radiation pressure. In order to accomplish these experiments accurately, all other disturbances, except those which it is desired to measure, must be eliminated. Such disturbances, for example, may take the form of motion of the liquid. The motion can be eliminated by placing the torsion balance in an enclosure made of a thin film of celluloid or similar material, which does not allow it to pass through but does transmit the ultrasonic waves. The measurements cannot be made entirely exact, since the presence of the balance itself affects the radiation field.

For this reason optical methods have been applied. In these methods a beam of light is transmitted through the liquid under test and the absorption estimated from the intensity of the diffracted rays.

More recently, the amount of absorption has been investigated by the pulse method. In this system a pulse of given amplitude is sent through the medium that it is desired to investigate and the peak-to-peak amplitude of the pulse is measured at various points along the path. The energy at each point is proportional to the size of the pulse, and the decrease in size is a measure of absorption.

In all cases the measurements that have been published show a sharp divergence from the classic theory of ultrasonic absorption, and it is not exactly clear as yet why this is so.

In ultrasonic cells absorption is often added to prevent unwanted energy from being transmitted in other than the desired direction.[1] This can be done by adding resistances to the system in order to attenuate unwanted signals. The resistances take the form of gratings, absorbing liquids, etc.

*Classic Theory.* The common classical explanation of the absorption of ultrasonic energy is contained in the following description by Stokes. Stokes[2] and Kirchhoff[3] ascribed the absorption of sound to heat conduction and internal friction.

The resultant equation is

$$2\alpha = \frac{4\pi^2 f^2}{c^3 \rho_0} \left[ \frac{4}{3} \eta + \frac{(K - 1)}{Cp} k \right]$$

where $\eta$ = coefficient of viscosity
$f$ = frequency of the wave
$\rho_0$ = mean density
$c$ = velocity of sound
$K$ = ratio of the specific heats
$C_p$ = specific heat at constant pressure
$k$ = thermal conductivity

The quantity $2\alpha$ is the intensity absorption coefficient of a plane wave and is defined by

$$I = I_0 e^{-2\alpha x}$$

where the intensity $I_0$ falls to a value $I$ after traveling a distance $x$.

Stokes defined the viscosity contribution as

$$\alpha_1 = \frac{8\pi^2 f^2 \eta}{3c^3 \rho}$$

and Kirchhoff the amount due to heat conduction as

$$\alpha_2 = \frac{2\pi^2 f^2}{c^3 \rho} \frac{K - 1}{Cp} k$$

Generally speaking, the amount of absorption is not a problem in any ultrasonic system used for testing, measurement, or agitation. However, it is very important in signaling systems where large distances are to be transversed by the ultrasonic waves. Experimental values are usually several hundred times those computed from these formulas.

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[1] *Ibid.*

[2] G. G. Stokes, *Phil. Trans.*, **8,** 287 (1845).

[3] G. Kirchhoff, *Pogg. Ann.*, **134,** 177 (1868).

**Motional Impedance.** The electrical impedance of a circuit driving an ultrasonic transducer is influenced by the vibration of the transducer. Because of this vibration a back emf is generated and impressed on the circuit, just as in the electrical case. This back emf will act to oppose the impressed one, and as a result there will be a change in the circuit impedance. The change is referred to as the *motional impedance*, and the amount that is generated is an indication of the efficiency with which the transducer is vibrating.

**Beats.** Beats can be produced by having two sources of energy of nearly the same frequency physically close to each other. The resulting ultrasonic wave will be the result of superposition. The energy of the two waves is added, and a resultant wave produced whose amplitude varies with that addition. The difference in frequency between the two sources is the number of beats produced.

Beats may occur between electrical and ultrasonic signals in certain cases, *i.e.*, between electrical oscillations themselves and those signal variations caused by the ultrasonics. It is important to realize this when designing instrumentation, since the beats may vary in intensity so that a signal is produced which is very similar to that produced by a discontinuity in the ultrasonic path itself. This is especially true in continuous-wave systems when tanks containing liquids are used.

Although the two waves beating with each other are of high frequency, the beats produced may actually be sonic if the frequency difference is of that order.

Beats are sometimes used as a method of indicating the presence of energy or to measure the frequency of an unknown wave.

**Doppler Effect.** It can be demonstrated that the frequency of a source of energy seems to vary when either the source or its receiver is moving with respect to the other. This is known as the *Doppler effect* and has many interesting manifestations in nature. If the receiver moves toward the source, the frequency rises; and if the motion is away from the source, the frequency becomes less.

The Doppler effect can be used as an indicator for ultrasonic waves by noting the change in frequency as an ultrasonic source approaches a reflecting surface. Such a change may be in the form of an audible or an ultrasonic indication.

**Cancellation Effects.** Like other types of waves, ultrasonic ones exhibit cancellation effects. In other words, waves of the correct phase may add up to zero displacement. Such effects can be noted experimentally if two sets of holes are drilled a quarter wavelength apart in a block of material and the amount of reflecting surface is balanced by drilling more holes in one or the other group until there is no reflection indicated from the combination. The energy reflected from each is then canceling out that from the other.

Cancellation effects do not ordinarily occur in natural situations to such an extent that absolutely no resultant energy is reflected, since the reflecting surfaces are usually not perfectly regular or spaced exactly the proper distance apart.

**Cavitation.** As ultrasonic waves of high intensity pass through a liquid, bubbles may be observed to collect at certain points. These bubbles seem to be due to gas that is expelled from the medium. This reaction is referred to as *cavitation.*

The bubbles will tend to form at certain points where the ultrasonic waves have their nodes and may be very well defined. Generally, the more volatile the liquid the larger the amount of bubbles that collect. Hydrostatic pressure[1] seems to be a controlling factor of the action.

The amount of energy necessary to cause cavitation can be measured experimentally. The gas expelled from the medium has been determined to be either wholly air or a very high percentage of it.

The action does not seem to indicate any actual rupture of the liquid itself, but the forming and destruction of these bubbles have a strong effect upon agitation systems and form the basis of many of the phenomena associated with them.

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[1] R. W. Boyle, Ultrasonics, *Science Progress*, **7**, No. 89 (1928).

# CHAPTER III

# CRYSTALS FOR ULTRASONIC USE

There are several possible means of producing ultrasonic waves. Of these, the most common and practical is the quartz crystal.

**General.** The most popular types of electromechanical converting systems are the piezoelectric and magnetostrictive ones, although there are also two other types, *viz.*, the electromagnetic and electrostatic. These last types are used in generating acoustic waves in air and are not of much interest in ultrasonics except possibly in sound ranging.

The piezoelectric effect is of greatest importance in certain types of ultrasonic work, although the magnetostrictive is also widely used and will therefore be discussed separately. The former effect occurs in several natural and artificial crystals and is defined as a change in the dimensions when an electric charge is applied to the crystal faces.

Quartz crystals have been widely used for generating ultrasonic vibrations in solids and liquids, since they are media that have a high mechanical impedance. Where the impedance is low, the ratio between the output and the charge applied to the vibrating crystal is too small for effective use.

Especially in ultrasonic work at the higher frequencies, where there may be contact between the transducer and a solid medium or where great power is not important, longitudinally or shear vibrating quartz crystals are still most commonly used.

Frequencies produced by quartz blanks cover a range from a few hundred kilocycles to about 15 mc when vibrating in a fundamental mode and are capable of producing very much higher frequencies when operating at a harmonic.

**History.** Professor Langevin was the first to apply the piezoelectric effect to the problem of ultrasonic generation when he was commissioned by the French government during the First

World War to find a means of locating enemy submarines, which at the time were attacking French vessels. He found, after considering the problem, that the piezoelectric effect made the quartz crystal useful for this purpose, and his patent[1] discloses the idea of a mosaic of crystals cemented between steel plates (Fig. 3-1) and used to generate and receive ultrasonic waves.

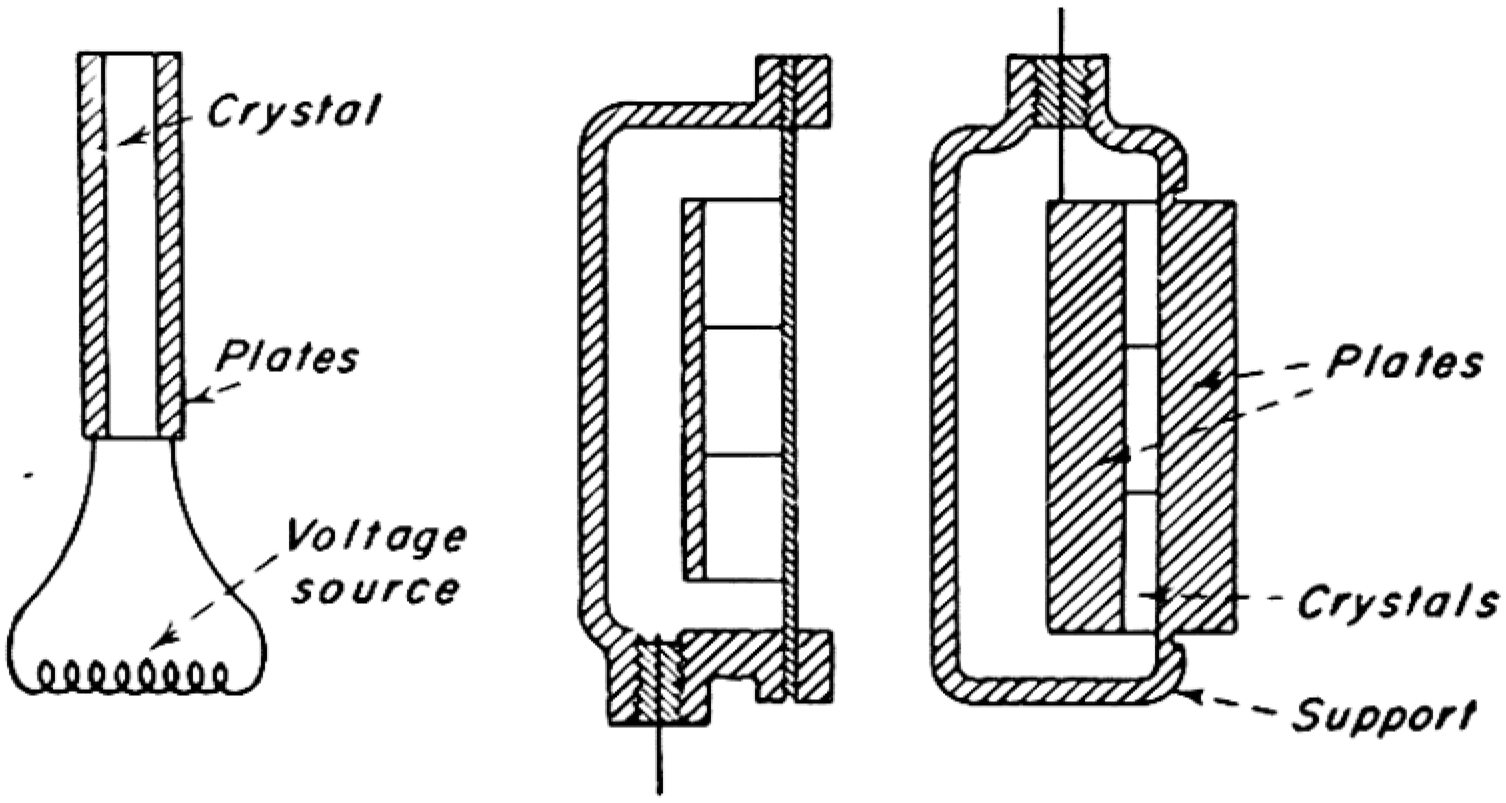

FIG. 3-1. Langevin transducers.

The quartz crystal has the property of expanding and sending out an ultrasonic wave when a voltage is applied to it, and it can also produce an electrical signal when it is mechanically vibrated. The device was not used during the war of 1914-1918 to any extent, since its development was not completed soon enough. However, since that time the quartz crystal has become the basis of many underwater detecting and signaling means, of listening systems, and of depth-finding devices. Of course, since the date of Langevin's patent a huge amount of additional experiment has been carried out.

Besides quartz, Rochelle salt is one of the principal materials used in the generation of ultrasonics, especially in the low-frequency ranges and for use submerged in a liquid, as in submarine signaling.

A. M. Nicolson[2] of the Bell Laboratories did pioneer work with the Rochelle salt crystal at about the same time that Langevin was working. The piezoelectric effect in Rochelle salt is considerably greater than it is in quartz. However, the units are much softer and therefore more subject to breakage and damage than quartz. On the other hand, in submarine work, the transducer is protected by its housing, and Rochelle salt can therefore be used.

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[1] P. Langevin, British Patent 145,691, 1921.

[2] A. M. Nicolson, The Piezoelectric Effect in the Composite Rochelle Salt Crystal, *Proc. Am. Inst. Elec. Engrs.*, **38**, 1315 (1919).

During the Second World War several other artificial crystals were developed, mainly for submarine work. These crystals have characteristics especially adapted to such applications.

From every point of view, durability, economy, ease of manufacture, and simplicity, the quartz crystal is the most desirable of all the types of generating units that may be chosen for ultrasonic work. The $X$ cut is the most commonly used, since it generates longitudinal, or $L$, waves. For the production of shear waves $Y$ cuts are also used, but this type of wave motion will not travel through liquids or gases, in which there is no shear elasticity, and for use with solids they must be coupled to the work by special means. For these reasons $Y$-cut crystals are not widely applied.

**The Quartz Crystal.** Natural quartz is an extremely stable material, both chemically and physically, and very hard (7 in Mohs' scale). It is usually found in the shape of a prism of six sides, with a pyramid attached to each end. If the points of these pyramids are joined by a line, that line is defined as the optical, or $Z$, axis.

The $X$ axes are also called the electrical ones and are defined by lines passing through the opposite corners of the crystal. There are therefore three $X$ axes to each natural piece of quartz. The $Y$ axes are perpendicular to the sides of the figure. There are therefore three of these also. Both of these axes are perpendicular to the $Z$, or optical, axis.

Plates or blanks can be cut to either of these axes (or in many other ways), and in each case they have certain definite characteristics. Blanks can be cut for fundamental vibration up to about 10 to 15 mc. Beyond this range they become so thin that they have a tendency toward mechanical failure. Accordingly, crystals for higher frequencies are cut at a subharmonic.

The crystals must have parallel faces and be polished free of all kinds of chips or cracks; otherwise they will not vibrate freely. Optical emery finish is usually satisfactory for ultrasonic work.

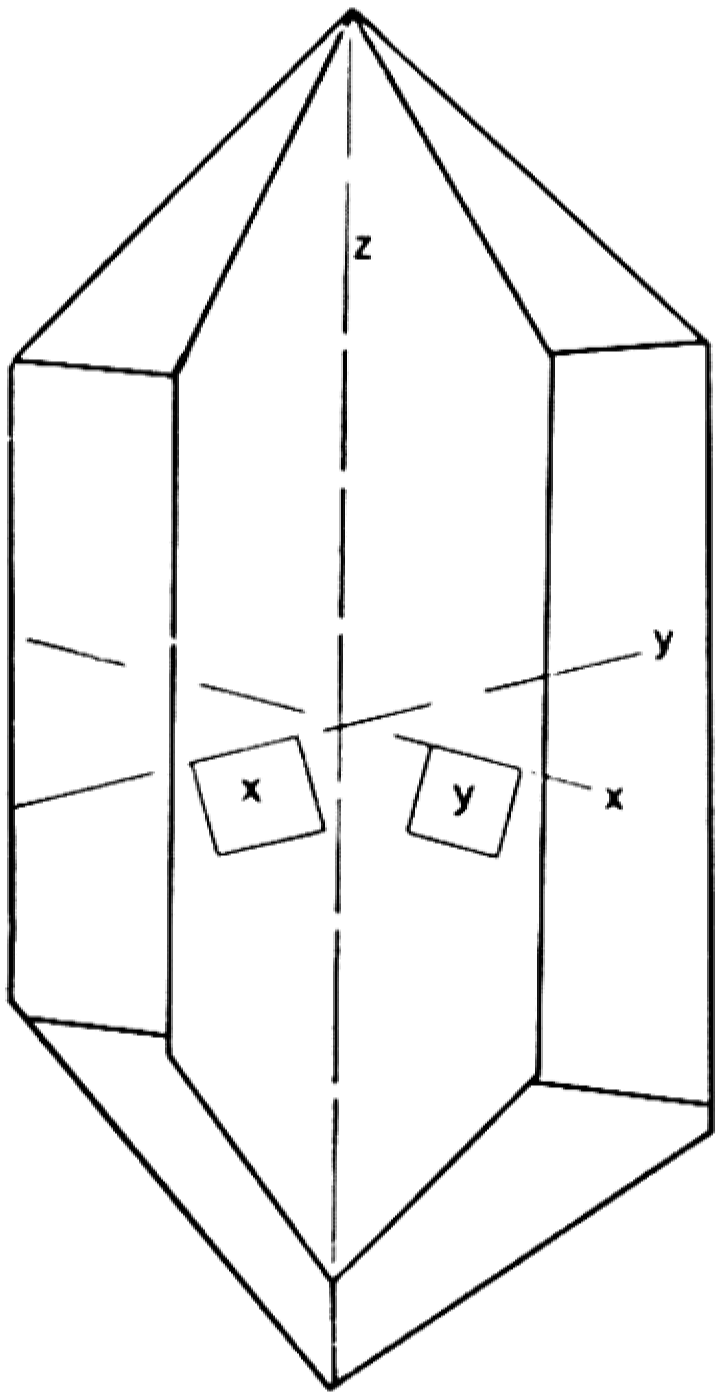

FIG. 3-2. The quartz crystal.

Figure 3-2 shows the shape of the natural quartz crystal and the orientation of the common ultrasonic cuts.

**The Piezoelectric Effect.**[1] The fact that certain crystals will develop an electric charge when a mechanical pressure or tension is applied was discovered in 1880 by the Curie brothers. This phenomenon was later named the *piezoelectric effect*. Their experiments showed that there was a direct proportion between the mechanical pressure and the resultant charge. Moreover, the sign of the charge changed when pressure changed to tension or vice versa.

The effect is present in many types of crystals, but it is most useful in quartz and Rochelle salt. However, as mentioned, a number of artificial crystals were developed during the late war, which are mainly designed for submarine signaling and are not suited for the transmission of ultrasonics into solids.

The polar axis of a quartz crystal is the point at which the maximum charge will appear. It is therefore also called the *piezo axis*. This axis can be identified by rotating the crystal. When the rotation is carried out about an axis perpendicular to the polar axis, the crystal is not symmetrical.

The polar axis is important because the blanks used in ultrasonics are cut at right angles to it to get the maximum effect. Moreover, the crystal differs at the ends of this axis optically, chemically, and physically. Etching produces different patterns, and stresses produce charges of different signs.

When a crystal is cut in the $x$ or $y$ direction, it has the characteristic that pressure on the $X$ axis produces a charge on the crystal surfaces perpendicular to that axis. This is known as the *longitudinal direct effect.* The transverse direct effect will produce the same charges that pressure on the $X$ axis would produce but will do it as the result of tension on the $Y$ axis.

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[1] P. Curie and J. Curie, Développement par pression de l'électricité polaire dans les cristaux hémièdres à faces enclinées, *Compt. rend.*, **91**, 383 (1880).

When tension is changed to pressure or vice versa, the sign of the effect changes but otherwise there is no electrical change. Therefore, if an alternating charge is applied at high frequency to the crystal, and if the crystal is properly designed to oscillate at that frequency, it will follow the applied field. The faces of the crystal will move with respect to each other; and if one face is pressed against the surface of a medium, ultrasonic waves will be produced and enter the medium and then travel through that medium (if, of course, the medium is able to support the propagation of ultrasonics).

It is not theoretically necessary for a crystal to vibrate or oscillate at its resonant frequency. Crystals can be driven at any frequency whatever, provided only that the power applied by the oscillator or generator is great enough. However, the amplitude of crystal oscillation is so much greater at resonance that crystals are rarely used at any other frequency except when there is some definite reason for doing so. A typical reason would be the necessity for thick plates at comparatively high frequencies in agitation. In such a case a low-frequency plate is driven at a higher harmonic frequency. In a like manner high-frequency crystals can be driven at lower frequencies. This is commonly done in resonance work where a crystal is driven over a range covering a group of frequencies all below its natural or resonant one. In this manner resonances in the medium are made to indicate without being influenced by resonance in the crystal.

Quartz crystals can be very sharply tuned to a particular frequency. The logarithmic damping is about $1 \times 10^{-4}$. Any material in contact with the quartz increases the damping, *i.e.*, broadens the tuning of the blank.

A crystal will vibrate in different directions or manners depending on its cut. These modes have been widely studied and can be understood by examination of Fig. 3-3. The first sketch shows the way in which a $Y$-cut crystal vibrates, and the second one, the way in which an $X$-cut crystal does. The crystal may also oscillate at any harmonic, usually an odd one. In harmonic vibration even more complicated patterns result.

Crystals do not ordinarily vibrate in one direction only, even though designed to do so. There is always sufficient movement in the other dimensions to be of practical importance. Thus, a crystal that is to vibrate in the $X$ direction must not be clamped rigidly about its edges, since in that case its vibrations will be strongly damped. For this reason crystals are ordinarily relieved in all other dimensions than the one in which vibrations take place. This may be accomplished by careful design of the support. In the case of resonance measurements just the opposite is true, since only one type of wave must be allowed to exist. The crystal is therefore rigidly clamped in such a manner that all other types are prevented. For these and other reasons the pattern of vibration on the face of the crystal may be extremely complex. These are referred to as *Chladni patterns.*

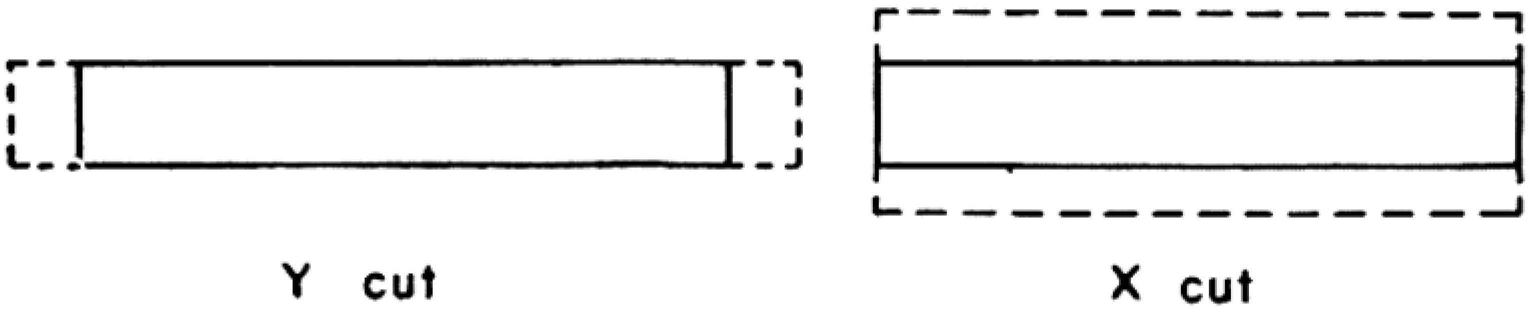

FIG. 3-3. Crystal motions during excitation.

**The Reverse Piezoelectric Effect.** Lippmann predicted the reverse effect in 1881 and pointed out that not only will vibrating the crystal mechanically cause electric charges but that placing electric charges on the crystal will produce mechanical vibrations. This action is sometimes called the *longitudinal reciprocal* or *transverse reciprocal effect*, depending upon whether the crystal acts in the $x$ or $y$ direction. Moreover, when the sign of the applied charge is changed, contraction changes into expansion and vice versa. The amount of contraction and expansion was calculated by Voigt,[1] who showed that the longitudinal effect in quartz is dependent on the voltage applied, but not on the crystal dimensions. For 3,000 volts applied in the $x$ direction, the expansion was $6.36 \times 10^{-7}$ cm.[2] Such a small effect is naturally very difficult to measure. However, methods of doing this have been worked out in the literature.

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[1] W. Voigt, "Grundlagen zu einer allgemeinen Theorie der piezo und pyroelektrischen Erscheinungen an Kristallen," 1890.

[2] Bergmann, "Der Ultraschall," Berlin, 1942

The entire action of a crystal transducer therefore consists of the direct effect, *i.e.*, the production of vibrations of ultrasonic energy when the crystal is excited electrically, and the inverse effect, *i.e.*, the production of electrical signals when mechanical forces are applied to it. These two effects form the basis of many ultrasonic systems.

**Some Theoretical Considerations.** The classic theory of the piezoelectric effect may be found in the literature. However, a few facts that may be of interest are abstracted here.

As indicated, when a crystal is subject to a compression or expansion in the proper dimension, an electric charge appears on it. This charge is directly proportional to the pressure.

The amount of charge that appears is also determined by a characteristic of the crystal, known as *piezoelectric modulus*, that has been experimentally measured. If $\delta$ is the modulus for quartz, it is

$$\delta = 6.32 \times 10^{-2} \text{ esu/kg}$$

In both the direct and reverse effect this modulus is an indication of the efficiency of electromechanical conversion. The modulus is a constant and remains identical for any one material.

However, although the charge is proportional to both the pressure and the modulus, it is essentially independent of the crystal thickness, temperature, and area over a wide range. In other words, the basic relationship is that the field intensity is directly related to strain. This is very fortunate, since variations in temperature or area often occur in practical work and it is preferable that the variation in ultrasonic energy caused by these factors be a minimum.

Ny Tse Ze[1] examined the limitation of the piezoelectric effect. He discovered that the changes in the dimensions in quartz were proportional to the applied voltage until an application of about 3,000 volts. Above this point the change in dimensions reached a limit. He also discovered that the temperature should not exceed 300°C. Piezo activity is practically constant between the temperatures of 20 and 300°C, but above that upper limit the piezoelectric modulus falls off sharply. The maximum value of the modulus occurs at about 200°C. At about 573°C, this entire piezoelectric effect stops. When crystals are used under extreme heat, they must be heated gradually; otherwise they will shatter.

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[1] Ny Tse Ze, *Compt. rend.*, **184,** 1645 (1927).

Ny Tse Ze also stated that the highest possible frequency using a quartz plate at its fundamental was 50 mc, for which the plate thickness was 0.055 mm. Higher frequencies were possible if partials (harmonics) were used. Crystals of this order of thickness are very fragile; and unless the crystal is faced with a protective material, a more practical limit is 10 mc.

These limitations dictate where crystals can be used. It is sometimes desirable, for example, to send vibrations into masses of hot steel. Granted that the materials by which the crystals are mounted will allow it, work up to these limitations is possible. Generally the crystal mounting is more critical in respect to temperature than the quartz itself.

**Temperature Coefficient.** Within the limits of temperature already cited, there are variations in frequency due to temperature changes (besides the change in the piezoelectric modulus). The amount of variation is usually expressed as a coefficient and gives the frequency excursion caused by a change in temperature of 1°C. It is desirable that there be a minimum amount of frequency variation caused by temperature.

When the change is in the direction of higher frequency, it is called *positive;* and when it is in the direction of lower frequency, it is called *negative.* Most *X*-cut crystals have a negative temperature coefficient of about 15 to 25 cycles/mc/°C. *Y* cuts vary more widely, from $-20$ to $+100$ cycles. Other cuts have been developed with a much lower coefficient, but they are not widely used in ultrasonics, since they are not efficient as transducers.

The change in frequency is not a serious problem in ultrasonic generators, since most of them work satisfactorily within wide frequency variations. A few hundred or even thousand cycles of frequency variation will not affect either the ultrasonic output or any other characteristic of the waves to an appreciable extent.

However, as indicated in the previous section, ultrasonic output may drop with increase in temperature. Such an increase may often occur in agitational systems or in test systems where the crystal is placed on hot steel, etc. Under those conditions serious loss of energy may result.

The crystal is usually cemented in some way to its mounting. If the cement is affected by heat, it may become loose and the crystal dislodged.

The temperature coefficient is given by the formula

$$\text{Temperature coefficient} = \frac{\Delta f}{(f_0 T_{\text{max}} - T_{\text{min}})}$$

The coefficient is solved for in cycles per second per megacycle per degree centigrade. The change in cycles between the maximum and minimum temperature is $\Delta f$. The nominal frequency of the crystal in megacycles is $f_0$.

There are also cases where the frequency of generation must be controlled very closely, as in systems for the measurement of the physical properties of materials. In such cases the temperature of the whole ultrasonic system must be closely regulated.

**Harmonics.** The thickness of the crystal blank is inversely proportional to frequency; *i.e.*, it becomes thinner at higher frequencies. As already indicated, when it is desirable to operate at more than about 10 to 15 mc, a crystal of a lower resonant frequency must be used at one of its harmonics or partials in order to get mechanical strength. Under such conditions the amount of energy supplied by the crystal becomes appreciably less. However, since the crystal is thicker and therefore more sturdy, it can be excited more heavily than one resonant at the frequency, and the loss in energy can be partially compensated for in that manner. This is true, however, only in high-power systems. In test and signaling systems the crystal is driven at such a low power level that there is never any question of a power limitation because of the thickness of the crystal. Moreover, it can be shown both theoretically and practically that only the odd harmonics can be excited very strongly because of cancellation of the even ones in the crystal itself.

Harmonics may be of some value where it is desirable to operate a setup at several frequencies without changing crystals. One crystal can then be driven at several different frequencies. Experimentally, it seems easier to drive a high-frequency crystal at low frequencies than a low-frequency crystal at high ones. It is also possible to shock a crystal with a sharp step of voltage and allow it to oscillate or ring at its own natural frequency.

In resonance systems the crystal is always operated over a wide frequency range and the resonance points noted. In such cases the crystal should always be above the highest frequency at which it is desirable to operate. The output will naturally vary with frequency, but the resonance points are sufficiently well marked to make them apparent. The crystal should not have any resonances, either fundamental or harmonic, within the operating range. *X* cuts are used.

For example, a crystal of about 3 mc is satisfactory for work resonant at about 1 mc, one of 6 for work at 2½, etc.

**Crystal Shapes.** Crystals may be square, round, oblong, or, in fact, any convenient shape. However, square and round ones have been most widely used because they are easily procured and handled and operate satisfactorily. Round crystals are probably somewhat superior from the point of view of breakage, since they do not have sharp corners which may chip off. Round crystals also radiate more strongly, since the corners of a square crystal do not seem to put out much power. Holders are easier to make, and polarization effects are less apparent.

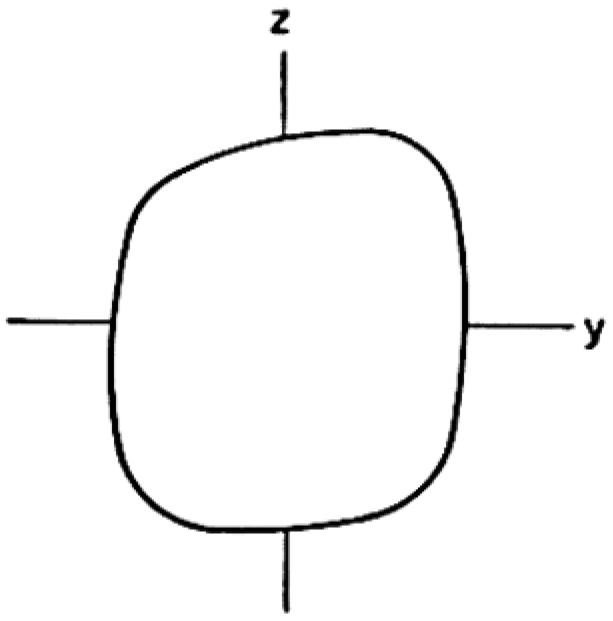

FIG. 3-4. The Straubel contour.

When the crystals are made very long and thin, other types of vibration may become apparent. The blanks are moreover very fragile.

The Straubel contour[1] is the name given to a special type of cut that is supposed to give greater output. In this type the shape of an *X*-cut plate is designed so that the edge of a blank is always at a distance from its center which is proportional to the square root of the elastic modulus. Such a plate is shown in Fig. 3-4.

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[1] H. Straubel Schwingungsform und Temperaturkoeffizient von Quarzoszillatoren, *Z. Hochfrequenztechn.*, **38,** 19 (1931).

The cross-sectional dimensions of a crystal plate are not usually considered in designing crystals for low-power systems, although such dimensions do have some influence on the crystal.

However, this influence is so slight that it can be ignored and satisfactory results obtained. In other words, a 5-mc crystal may be ½, or 1 in. square or have a diameter of 1 or 2 in. but be designed (in thickness) by the same considerations.

**Design of the Ultrasonic Crystal.** *Longitudinal Waves: X-cut Crystals.* An *X*-cut crystal is usually mounted with an electrode on each face for impressing the exciting voltage on the blank and for making contact with the charge produced by vibrating the crystal by ultrasonic waves. For the fundamental frequency a longitudinal vibration occurs in the thickness dimension of the crystal. If $\lambda$ is the wavelength of the stationary wave that is excited in the quartz crystal because of its natural resonance, then the thickness of the plate

$$t = \frac{\lambda}{2}$$

The density of quartz is 2.654 g/cu cm. Young's modulus is $770 \times 10^9$ g/cm/sec$^{-2}$. The velocity of ultrasonic waves in quartz in this direction is

$$c = \sqrt{\frac{E}{d}} = 540 \times 10^3 \text{ cm/sec}$$

However, $\lambda = c/f$ and $t = \lambda/2$.

Therefore,

$$f = \frac{c}{t} = \frac{2{,}700}{t} \text{ kc/sec}$$

where $t$ is the thickness in millimeters.

Experimental values do not agree exactly with this statement, but come closer to

$$f = \frac{2{,}870}{t \text{ (mm)}} \text{ kc/sec}$$

$$= \frac{0.1126}{t \text{ (in.)}} \text{ mc/sec}$$

This difference is probably due to the fact that there is movement in other dimensions than the $X$ one. These movements produce shear waves and other effects not considered in the original formula.

*Shear Waves: Y-cut Crystals.* In the case of shear-wave crystals, the theoretical and experimental design formulas agree well, since there is little effect on the oscillations in the $Y$ direction due to thickness vibrations. The formula is therefore

$$f = \frac{2{,}700}{t\ (\text{mm})}\ \text{kc/sec}$$

where $t$ is the dimension in the $y$ direction. Or

$$f = \frac{0.0771}{t\ (\text{in.})}\ \text{mc/sec}$$

A list of crystal thicknesses and frequencies is given in Table 3-1.

*Design Considerations for Tourmaline.* Tourmaline lends itself to the production of higher frequency ultrasonic waves than quartz. The thickness of a plate for producing a particular frequency can be computed from

$$t = \frac{364{,}000}{f}$$

where $t$ = thickness in cms
$f$ = frequency

This results in a plate about 35 per cent thicker than quartz for the same frequency. The wavelength of the energizing electric wave is accordingly

$$\lambda = 82.5\ t\ (\text{mm})$$

where $t$ is the thickness of the tourmaline plate.

Plates that have a fundamental frequency of 150 mc have been reported.

The piezoelectric modulus of tourmaline is

$$5.78 \times 10^{-8}\ \text{cm}^{1/2}\ \text{g}^{1/2}$$

**Surface-wave Crystals.** In order to produce surface waves, a special $Y$-cut crystal must be used. The thickness of this crystal is computed in the usual manner for $Y$ crystals. However, the $X$ dimension is designed to be about seven times that thickness. Rayleigh waves will then be sent out over the surface of the part parallel to the $X$ axis (Fig. 3-5). This type of crystal may propagate other types of waves as well, especially shear ones, and it is difficult to distinguish one type of wave from another experimentally. However, crystals designed to these considerations operate satisfactorily for measuring and testing purposes.

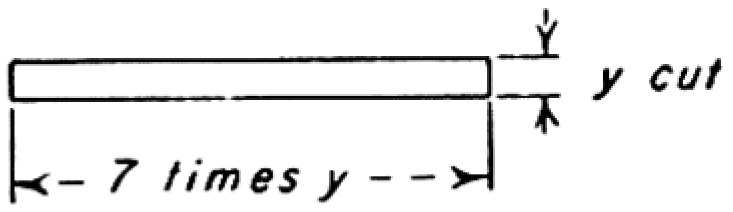

FIG. 3-5. Surface-wave crystal.

TABLE 3-1. TABLE OF CRYSTAL THICKNESS

$X$-cut. $f = \frac{k}{t} = \frac{0.1126}{t}$

| $f$, mc/sec | $t$, in. |
|---|---|
| 0.1 | 1.126 |
| 0.300 | 0.375 |
| 0.600 | 0.188 |
| 1.0 | 0.113 |
| 2.0 | 0.05763 |
| 3.0 | 0.0377 |
| 4.0 | 0.0282 |
| 5.0 | 0.0226 |
| 6.0 | 0.0188 |
| 12.0 | 0.0095 |

$Y$-cut. $f = \frac{k}{t} = \frac{0.0771}{t}$

| | |
|---|---|
| 1.0 | 0.0788 |
| 2.0 | 0.0394 |
| 3.0 | 0.026 |
| 4.0 | 0.0197 |
| 5.0 | 0.016 |
| 6.0 | 0.013 |
| 12.0 | 0.0065 |

**Directional Characteristics of Crystals.** The directional characteristics of crystals have already been considered under ultrasonic wave characteristics. These characteristics are integral to the crystal dimensions. The mounting of the crystal also strongly influences its directional characteristics (see Chap. IV).

**Crystal Plating.** Quartz crystals may be plated with faces of metal, usually aluminum, silver, gold, or chromium. These are deposited for physical protection and also to give surfaces on which the electric potentials can be impressed. The films distribute the charge over the face of the blank evenly. The geometry of the films should be such that the two faces do not come close enough to each other for electrical flashover to take place.

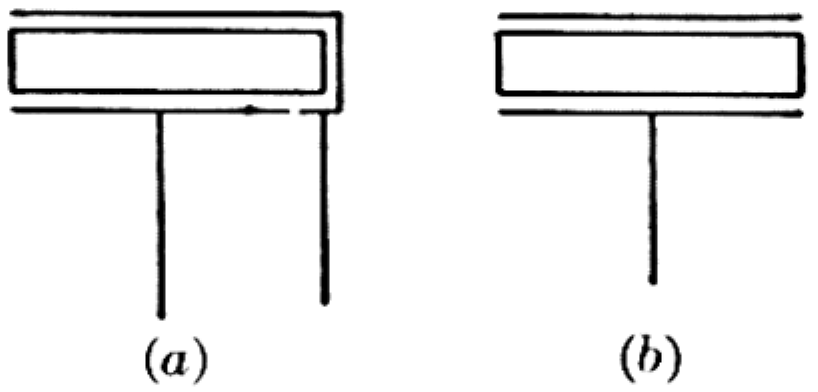

FIG. 3-6. Methods of plating crystals. (a) front face returned, (b) not returned.

The facing on the front face of the crystal can be returned to ground either by some form of connection to the work (if it is a conductor) or by a metal foil (when the medium is nonconducting). The front face can also be returned by bringing the plating around one of the corners of the crystal (Fig. 3-6).

There are various methods of depositing such films; but for most ultrasonic uses in which a tough surface is necessary, chrome surfaces are best. These are deposited by evaporation in the following manner similar to that used on astronomical mirrors:[1] First a thin coat of chrome is evaporated, then one of copper. The crystal is then removed from the vacuum apparatus and electroplated with copper and then with chromium. The exact thicknesses are not critical. However, the films should be kept as thin as possible. The parallelism of the plates should be carefully checked. The edges of the crystal can then be cleaned by grinding with an abrasive.

The final film should be checked for adhesion by scoring it with a sharp instrument. If it shows any sign of separation, it should be removed and the blank replated.

The cleaning of the crystal is very important. Platings will not adhere to a blank that is imperfectly cleaned. Techniques for satisfactory cleaning are therefore indicated in the context.

Foils may also be fastened to the crystal by gluing or cementing. A thin aluminum foil is sometimes fastened in this manner. Duco cement is satisfactory for such use. When this is done, it is important that the foil be fastened over the entire surface smoothly and evenly and that all excess cement between foil and crystal be removed. The foil should be porous, so that the cement thinner can evaporate.

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[1] R. C. Williams, U.S. Patents 2,079,784, May 11, 1937, 2,151,457, March, 1939

Leads may be fastened to the foil or plating by soldering or by spring contact.

Coatings are sometimes kept back from the edges of the crystals (see Fig. 3-7) in order to raise the electrical insulation between the two faces.

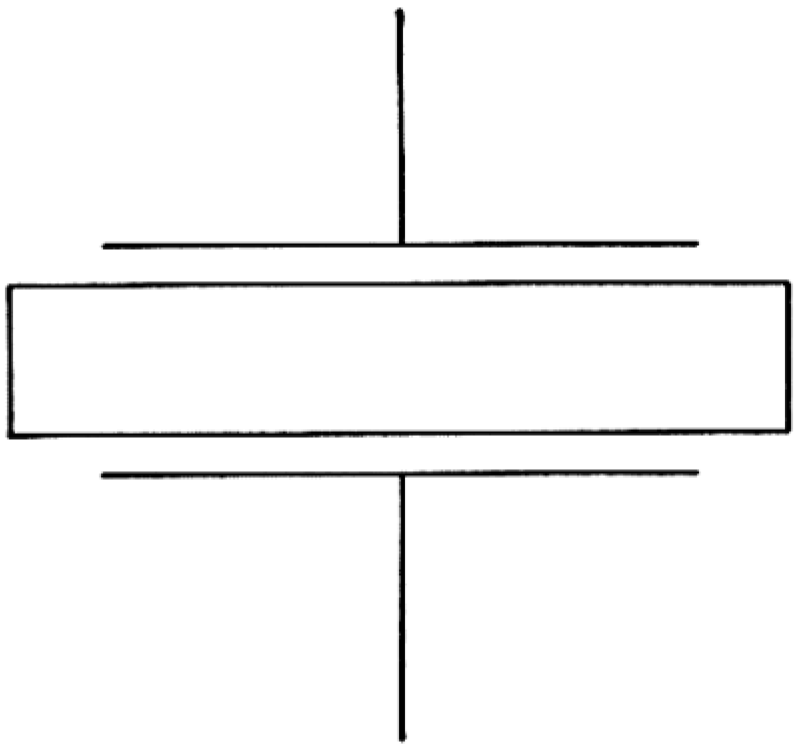
FIG 3-7. Plating for high voltage.

**Cleaning the Crystals.** Before a crystal can be plated, it must be very carefully cleaned, and often individual cleaning processes must be worked out. Dirt on crystals will be found to have individual characteristics depending on the blank's source, history, location, etc. One such cleaning process is as follows:

The crystals are placed in a solution of sulphuric acid and potassium dichromate, which is made up in a ratio of 40:1. The solution is then brought to a boil and allowed to continue boiling for 5 min. It is then cooled, and the crystals rinsed in distilled water.

The crystals are then boiled in potassium hydroxide for about 3 min and rinsed again in distilled water. The crystals are then boiled in distilled water, then in ethyl alcohol Finally they are dried on a wire screen.

It will be seen that the cleaning procedure is involved. However, its importance warrants the care taken. As already indicated, individual variations in the procedure will suggest themselves to each experimenter.

**Facings for Crystals** Having a steel face or one of other material over the front of the crystal is obviously of great value in prolonging its life. The use of such plates covering the face of a mosaic of crystals has been common practice in the field of submarine signaling, where various types of mosaics were used as early as the First World War.

The covering plates are generally of two basic types. In the first type the steel facing and the crystal are cemented together in such a way that they form a single vibrating system that operates at a certain specific frequency. These are described as *compound oscillators.*

In the second type a piece of steel a few thousandths of an inch thick is placed over the crystal or behind it. However, the crystal continues to oscillate at its original resonant frequency or at least very near it. This gives the system much greater physical strength but somewhat less ultrasonic output, although not so much less as to be useless. The plates are fastened onto the crystal by soldering or by a cement or wax such as de Khotinsky. Wax is easy to use and is completely satisfactory. The wax is melted on a hot plate, while the holder and crystal are both heated gradually to the melting point of the wax. It is advisable to have a minimum thickness of cement between the holder and the crystal. The crystal and plate are then pressed together while hot and gradually brought back to room temperature. Care should be taken that there are no bubbles in the cement or spots where crystal and plate do not adhere.

**Ultrasonic Output.** Sokolov made an investigation of various frequencies of oscillation from 10,000 cycles to 130 mc to determine their use in agitating molten metals ultrasonically in the metal industries. The results immediately following are largely his.

A crystal transducer has an ultrasonic output that is proportional to the square of the amplitude of oscillation and, of course, to the cross-sectional area of the crystal. Sokolov stated that the greatest possible mechanical output was obtained from plates of 16 to 20 sq cm. Plates from 4 to 8 sq cm were also tried. The larger the plate the more easily it is destroyed by excessive vibration because of its more inhomogeneous nature. Limitation to the output is set by the point at which the crystal ruptures.

For maximum output the faces of the crystal should be polished and the edges square. (This does not refer to the shape of the blank.) A minimum of damping should exist in the support.

An oil with high insulating properties to voltage such as a transformer oil is the optimum medium in which to apply the energy. From 2 to 3 kv can be applied in such a medium to a plate only 1 mm thick.

It is possible to get 150 to 200 watts of ultrasonic energy from a crystal plate 5 mm thick, with other dimensions optimum. The energy is measured either as heat output in the bath itself or by measurement of the power used in the plate circuit of the agitating oscillator.

The oil above the plate itself is thrown up in a jet about 10 to 15 cm high. Occasionally, drops of oil will be thrown as high as 40 cms. The size of the droplets and the shape of the jet of oil are a function of the frequency. As the frequency gets higher, the jet of oil becomes narrower and narrower and the size of the drops becomes smaller. At several megacycles the oil becomes very fine mist.

Small bubbles of gas form in the center of the oil bath, and intense heat is generated there. A test tube of material can be inserted there for agitation and will be violently shaken.

In order to keep the voltage from jumping between plates, the plating is usually kept back from the very edges of the crystal. Supporting the crystal is the biggest problem. In order to have intense agitation in the oil, the electrodes should be sputtered or evaporated and as thin as possible.

Bergmann mentions other experiments in which 300 watts of ultrasonic energy was generated and measured calorimetrically. Since no energy can escape from the oil, it is entirely turned into heat, and the measurements are therefore possible. In those experiments 39 kv were impressed on the crystals.

As far as testing or signaling is concerned, the power-output problem is a minor one, since a very small amount of power is needed, and therefore no special design is required. More considerations of power output will be discussed under agitational systems.

**Crystal Combinations.** Crystals can be mounted singly or in mosaics. They can also be stacked for greater output. When they are stacked, they are cemented together with the faces of the same polarity in the same direction. In stacked crystals the output seems to add; *i.e.*, four crystals give four times the output.

The systems are shown in Fig. 3-8. If the crystals are not aligned correctly as to polarity of vibration, the unit will not operate efficiently. All faces in the same direction must be positive or negative simultaneously, and all vibrations in the same direction occur at the same instant. Experimentally, stacked crystals do not add their power output arithmetically, but very great increments of power nevertheless occur.

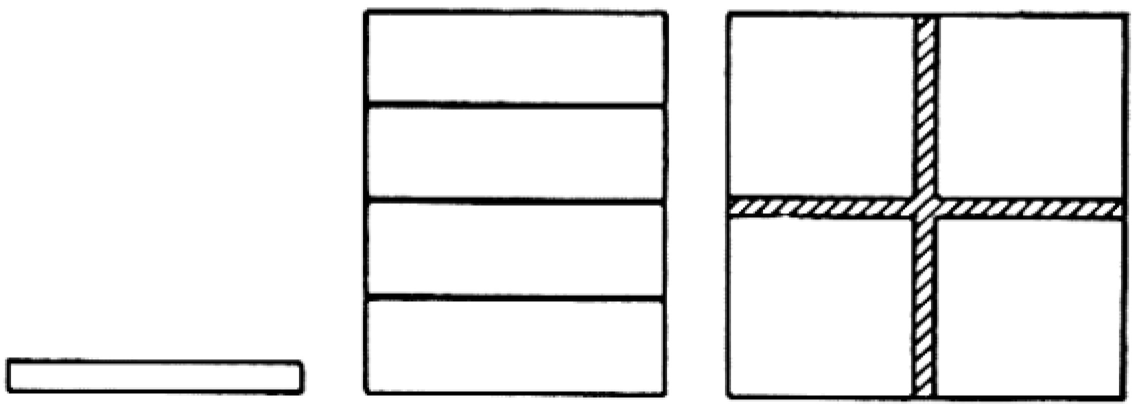

FIG. 3-8. Crystal combinations.

Mosaics of crystals add to the directional qualities as well as to the power output, since the spreading of the beam is computed for a mosaic as if it were a single crystal. Moreover, since the cross-sectional area is greater, the output is proportionately greater.

However, the stacked crystals give a more concentrated beam, at least when close to the transducer, since the beam starts as the projection of only one crystal rather than as that of several. It is only when the wavelength becomes of an order of size comparable to the area of the transducer that larger areas, *i.e.*, mosaics, result in more concentrated beams.

**Compound Oscillators.** A compound oscillator is a transducer made up of a combination of steel or other plates and quartz crystals. Usually the steel is fixed to both faces of the quartz. Either a single crystal or any combination of crystals can be used.

When the system is correctly fastened together with very thin layers of glue and with no discontinuities or air bubbles, it may be considered as a unit following the general rules of crystal design. Both longitudinal and shear waves can be produced by compound oscillators.

The material chosen for plates should have an ultrasonic velocity rating as close as possible to that of quartz. Naturally, there should be a minimum of damping in the entire system.

Mosaics of crystals may be used for greater output. Generally, the larger the surface the greater the output.

The design formula for a compound oscillator is

$$f = \frac{c}{2t}$$

where $f$ = frequency
$c$ = velocity
$t$ = thickness

Steel plates have been satisfactorily used in combination with quartz to form compound oscillators. Experimental values coincide well with the formula.

In other words, a compound oscillator for 5 mc would have a thickness that is the same as a 5-mc crystal if the velocity in the metal plates were the same as that in the quartz. When the plate velocity is different, corrections in the dimensions of the oscillator must be made, so that the whole unit is a half wavelength thick.

Sokolov[1] investigated both the frequency characteristics and spectra of such oscillators and explored their surfaces, mapping the face patterns by connecting those points which showed equal amounts of oscillation. Fundamental frequencies agreed with the values calculated. He also found evidence of complex partials that were different for different types of facings. The complex frequency response caused by the metal plates is due to the fact that they affect both the over-all transducer density and also its modulus of elasticity.

The equivalent circuit of such a transducer may be deduced and consists of a condenser in series with a parallel combination of a condenser across an inductance, resistance, and capacity in series.

Compound systems can be driven with such great power that the crystal and plates will be torn apart. However, this is unlikely except in agitational systems or submarine signaling. The compound plate is used only in high-power ultrasonic generators.

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[1] S. Sokolov, "Ultrasonic Oscillations and Their Application," Electro Technical Institute, *Leningrad,* June 25, 1935.

**Indicator for Elastic Oscillations.** It is sometimes necessary to explore the surface of the crystal or some other ultrasonic field to determine how the deformation is distributed and what the frequency characteristics are. This can be done with a second crystal connected to an amplifier, but in most cases the area of the face of the exploring crystal is so great that it tends to integrate a large amount of the ultrasonic field. An instrument for such exploration can therefore be designed as follows.

A plate is cut from a Rochelle salt piece, polished, and placed between two brass electrodes. These electrode surfaces are also optically polished, and a pointed glass rod is firmly fixed with shellac to one of the plate surfaces. Both the Rochelle salt and the electrodes are wet with transformer oil so that ultrasonic energy will easily pass through them. One electrode is then grounded, and the sharpened tip of the glass rod is placed vertically on the surface of the field or crystal to be explored. This tip covers a very small area, and detailed readings are therefore possible. The movement of the glass rod is coupled into the Rochelle salt crystal, which is connected to an amplifier. Rochelle salts used for this purpose should have the largest possible area, and all parts must be very well polished. The output of the unit is calibrated suitably.

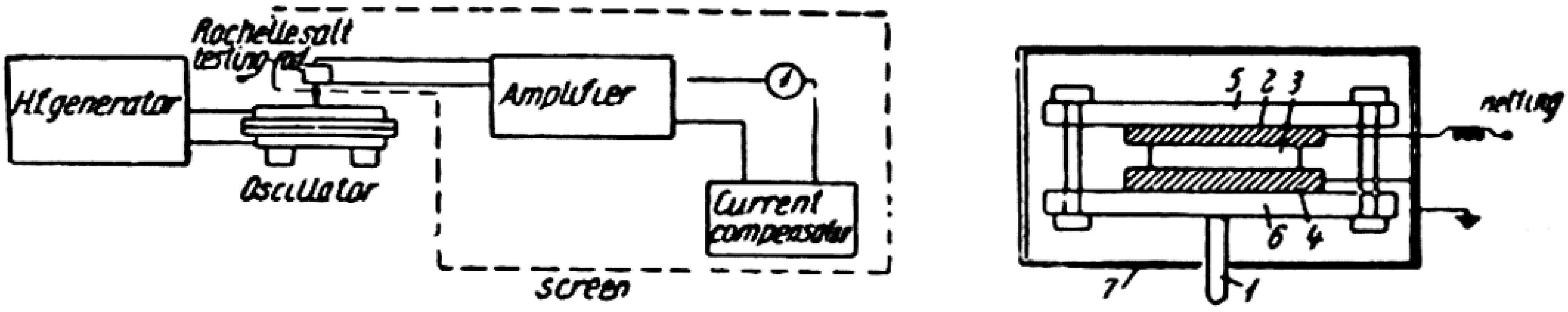

FIG. 3-9. Indicator for exploring ultrasonic fields: (1) rod, (2,4) plating, (3) crystal, (5,6) insulation, (7) screening.

The system is supported in a metal box from which only the end of the glass rod protrudes. Glass is used for the pickup because it does not conduct electricity. A device for such use is shown in Fig. 3-9.[1]

**Curved Crystals to Fit the Work.** Many parts into which it is necessary to transmit ultrasonics have peculiar shapes and forms. For example, they will very commonly be curved. Such parts as pipes, tanks, and shafts, fall into this category. In many cases where the piece of material is of radically broken shape, the physical dimensions make it difficult, if not impossible, to make satisfactory contact with the work.

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[1] *Ibid.*

However, in other parts there are smooth curves or changes of contour on which it is impossible to place a flat crystal but which can be compensated for by fillers or by curving the crystals. For example, a crystal may be ground to fit a shaft with an outside diameter of 10 in. and will transmit ultrasonic energy into it very well. As the curvature becomes sharper, it is more difficult to grind the crystal to fit. Grinding can be carried out satisfactorily on a lathe by mounting a piece of metal of the required diameter and grinding the crystal against it with fine abrasive material. The energy is propagated in essentially the same fashion as with flat crystals. There is, however, a focusing effect from the curved crystal.

A rule of thumb is as follows: If the medium is concave and of a diameter of 24 in. or greater or is convex and of a diameter of 18 in. or greater, flat crystals can be used. Otherwise the crystal must be curved to fit the work(see Fig. 3-10).

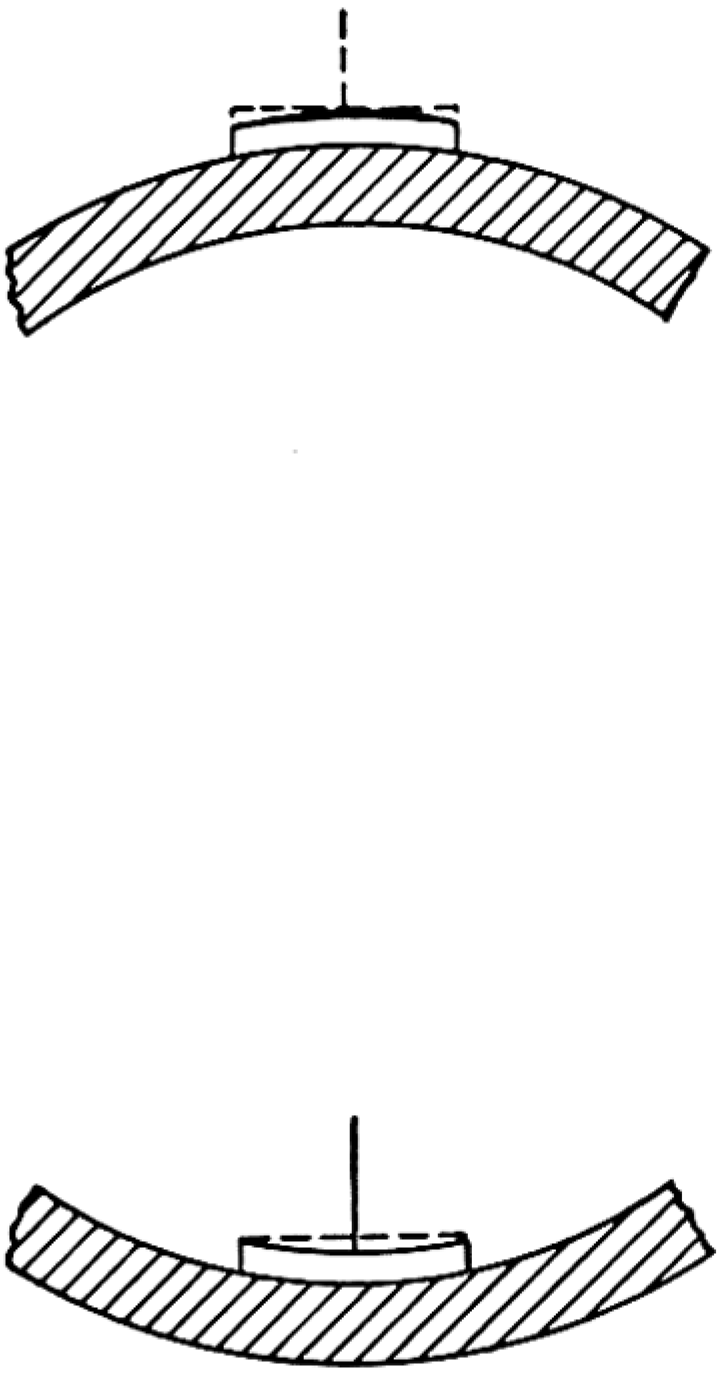

FIG. 3-10. Curved crystals to fit the medium.

The design of curved crystals is essentially the same as that of flat ones of the same frequency. The crystal may be curved on both surfaces or flat on one and curved on the other. The former situation is preferable. The diameter of the crystal should always be slightly greater than that of the work in order to provide a loose press fit.

**Focusing Ultrasonics with Curved Crystals.** Gruetzmacher[1] made the original experiments with the use of curved crystals for focusing a beam of ultrasonics. He was able to get greater ultrasonic action because of the focused, and therefore more concentrated, beam.

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[1] J. Gruetzmacher, Piezoelektrischer Kristall mit Ultraschallkonvergenz, *Z. Physik.*, **96**, 342 (1935).

The crystal blanks were ground so that the emitting face was concave. This caused the ultrasonic waves to focus at a point in the same way that a lens brings light to focus. Gruetzmacher also made the statement that the ultrasonic energy measured at the focal point of such a crystal was about 150 times that measured at a random sampling of points before the crystal.

A concentrated beam would presumably be very valuable for agitational work, where a great amount of ultrasonic output is necessary and where the amount of electrical voltage applied must be limited by considerations already mentioned. Figure 3-11 shows how ultrasonic energy is focused.

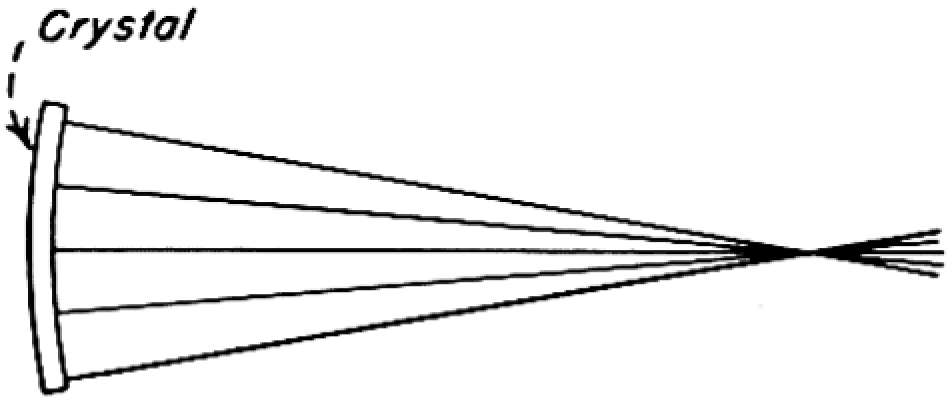

FIG. 3-11. Focusing.

More recent investigations[1] indicate that the energy measured in front of the crystal face depends not only on this factor of beam spread but also, for a given voltage, on the distance at which the measurements are taken. The energy at a given distance in front of a curved crystal is greater than that at the same distance from a flat one, because the curved crystal actually produces more ultrasonic output. At the sample point the angle of spread of the beam from the curved crystal might actually be greater than that from the flat crystal.

In other words, the greater concentration of energy in front of a curved crystal is due to two factors: (1) the focusing action and (2) the experimental fact that a curved crystal seems to give somewhat greater amplitude of ultrasonic output than a perfectly flat one for a specific voltage impressed. When a crystal is convex, however, there does not seem to be any evidence of greater output. Nevertheless, convex crystals are sometimes used to radiate wider beams. This characteristic is valuable in such fields as submarine signaling, where it is necessary to cover a wide field of search. Figure 3-12 shows a system for spreading the submarine search beam.[2]

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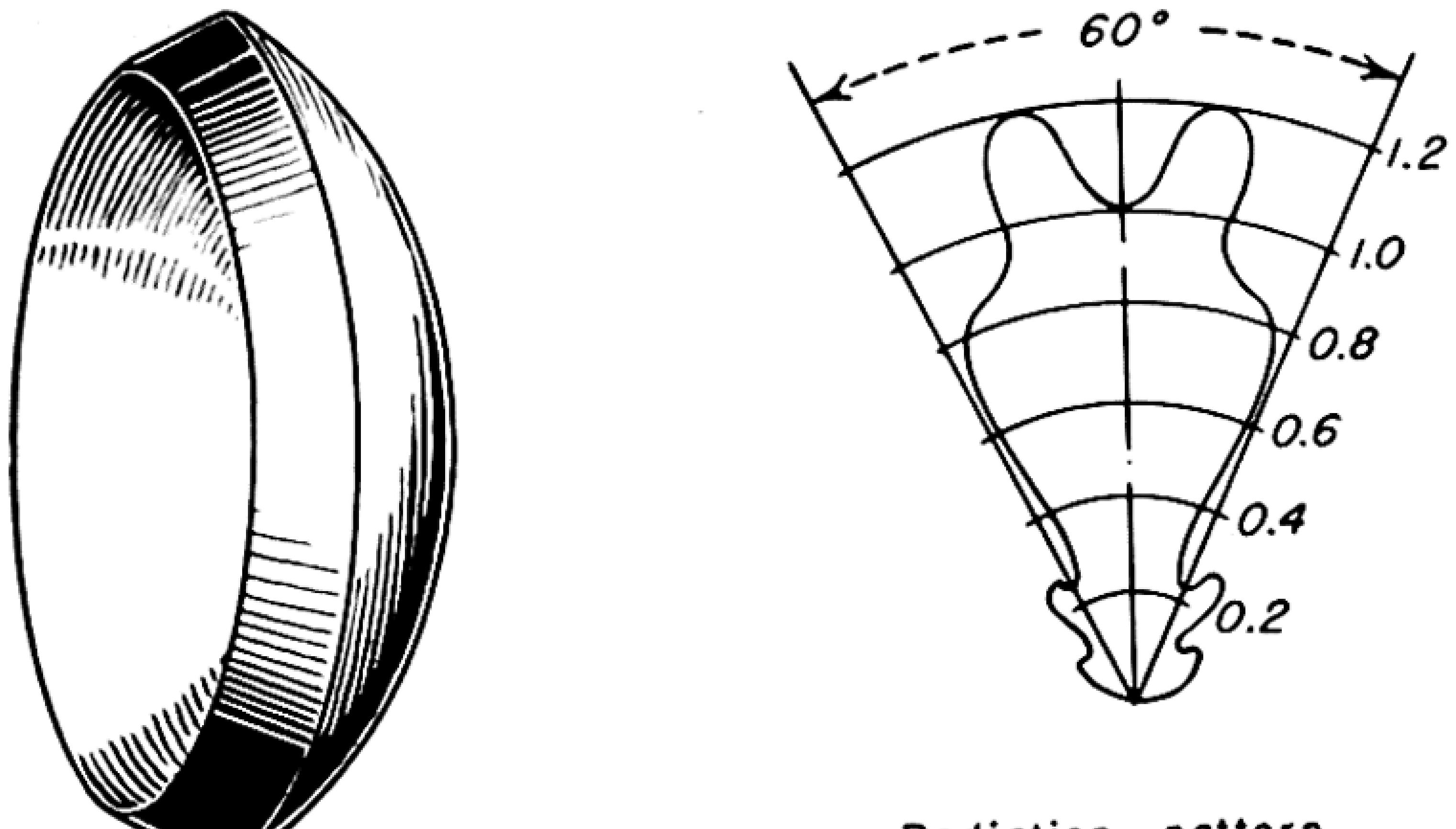
[1] L. W. Labaw, Curved Quartz Crystals as Supersonic Generators, *J. Acoust. Soc. Am.*, April, 1945.

[2] A. R. Morgan, U.S. Patent 2,399,820.



Radiation pattern

FIG. 3-12. Wide-beam crystal.

The focusing action of crystals, like that of lenses, may be expressed in diopters. This is an arbitrary term referring to a lens of 1 m focal length. Diopters can therefore be transformed into inches of focal length by a simple conversion:

$$\text{Diopters} = \frac{40}{\text{inches}} \text{ (focal length)}$$

This terminology is also used in calculating lenses for light.

The design of curved crystals for focusing applications is exactly the same as that of lenses for the same purpose, and a suitable text on optics would give such design data.

**Testing Crystals for Ultrasonic Activity.** The ordinary tests for crystal activity apply somewhat to testing blanks for ultrasonic activity, but the correlation is by no means perfect. A crystal may have a good deal of activity for the purposes of oscillator control, but the actual physical vibration will not be great enough to make the ultrasonic output sufficiently high for propagating ultrasonic waves. It is therefore sometimes necessary to test crystals for ultrasonic output, which can be done by placing them in a situation where they are actually used as

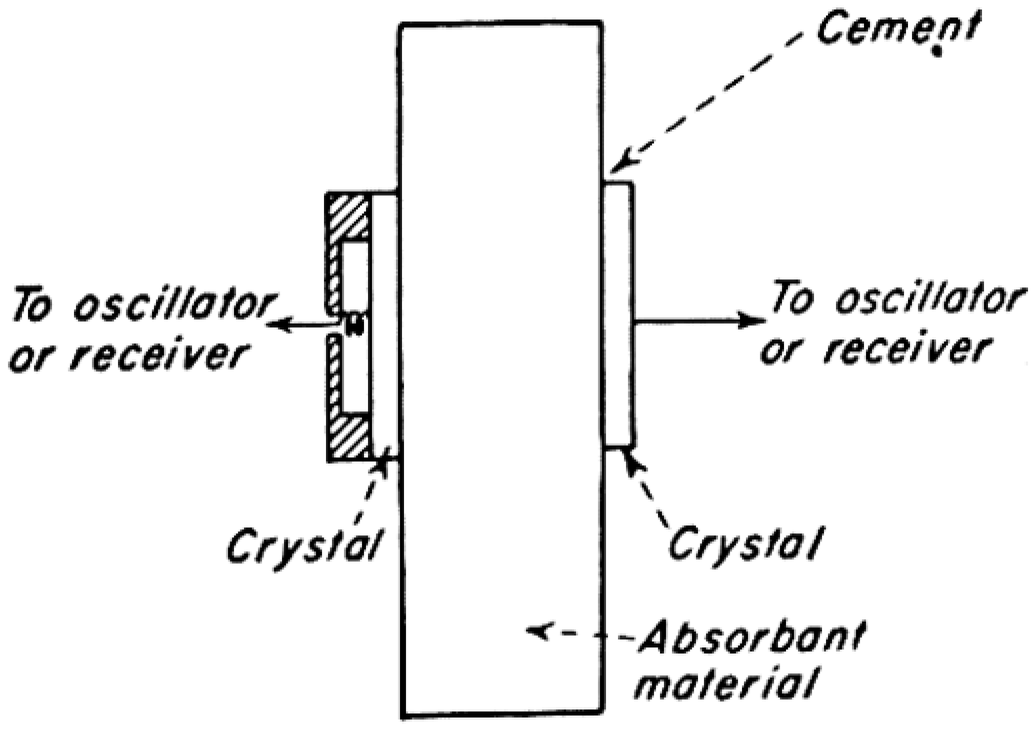


FIG. 3-13. Activity test apparatus.

ultrasonic generators and receivers. One such design is shown (Fig. 3-13). A jig supports the crystal to be tested. The blank under test is used as a transmitter to send ultrasonic energy through a medium of a highly absorbent character. A fixed crystal is cemented to the opposite side of the piece and is used as a receiver. This receiving crystal is then connected to a suitable radio-frequency amplifier, and the output of that amplifier is used to actuate a calibrated meter.

This unit may be calibrated against experimental evidence of ultrasonic energy or a known transducer and will provide an excellent indication of the output level. In a like manner, crystals can be rated for their receiving properties when a source of known activity is used.

**Rochelle Salts.** Rochelle salts are probably the most common type of crystal used in submarine signaling. They therefore merit further discussion. These crystals suffer from the fact that their mechanical structure is not sufficiently strong for them to be used in direct contact with anything but liquid media. However, the output of such a crystal is so much greater than quartz that it has found many applications.

Rochelle salt blanks are grown in a chemical solution. The solution is controlled in such a manner that its pressure or temperature changes; and when this is done, crystals form in the bath. Various special methods of producing such crystals have been widely examined and will be found in the literature.

Rochelle salt crystals are so soft that they can be cut with a piece of stretched damp string or with a rubber band pulled back and forth over them.

Any type of electrode can be used on blanks cut from the salt. Electrodes such as fine metal particles, metallic liquids, and foils have been widely used. The most common material is a metallic foil, which is cemented over the faces of the crystal.

Submarine signaling is one of the largest fields for the use of ultrasonics, and Rochelle salts have been more widely used up to the present in this field than any other form of crystal. When most of the units are used in this application, they are driven at a frequency other than the resonant frequency of the crystal. Various special ways of mounting such crystals have been developed; and when they are properly mounted, the crystal is much less subject to critical changes in temperature, etc., than when it is in its free form.

More complete studies of the physical and electrical characteristics of Rochelle salts may be found in the literature. Some of the effects noted are not as yet completely understood. However, these effects are not of great importance in ultrasonic work and will not be considered further here. The Rochelle salt crystal is limited in its practical application as far as ultrasonic work is concerned to the production of waves in liquids, and the special holders necessary for such operation will be discussed elsewhere.

The density of Rochelle salt is 1.775. Young's modulus for 45-deg $Y$ cut, which is often used ultrasonically $= 1.08 \times 10''$ g/sq cm. The characteristic impedance $Z_0 = 4.37 \times 10^5$, which is three times that of water.

**Other Types of Crystals.** As indicated, quartz has been the material most commonly used in ultrasonic work done in the past. However, during the war several artificial crystals were developed. For example, the *LH* type can be used from 100 kc to several megacycles. This crystal is one of a type that produces piezoelectric variations when subjected to hydrostatic charges. The crystal, like certain others, is called *pyroelectric* because a change in temperature also causes it to develop charges in the same manner that pressure does. The *LH* crystal has greater activity, in a theoretical sense, than Rochelle salts; but due to its capacity effects, it also has very great losses.

The ADP (ammonium dihydrogen phosphate) type is another artificial crystal developed for use under water (at about 50 kc).

Tourmaline would be very valuable ultrasonically except that it is expensive and extremely nonuniform in quality. Owing to this nonuniformity the blanks have a tendency to shatter easily. However, it operates at higher frequencies than quartz, since its thickness at any given frequency is greater, and it is about two and one half times as active as quartz.

**Cutting and Grinding Special Crystals.** Round crystals can be cut from square ones by means of a circular piece of tubing, with the ends tapered to about 0.010 in. This can be put in a slow drill press or on a lathe, and a grinding compound spread over the face of the crystal. The tubing will slowly cut into the quartz as it is gradually fed downward and as new cutting compound is introduced.

Curved crystals can also be ground on a lathe by cutting a curved template from a metal (see Fig. 3-14) and grinding the crystal against the template by introducing a grinding compound. Inside or outside diameters can be ground in the same manner. Both sides of such crystals may be ground, or only one side may be ground and the other left flat.

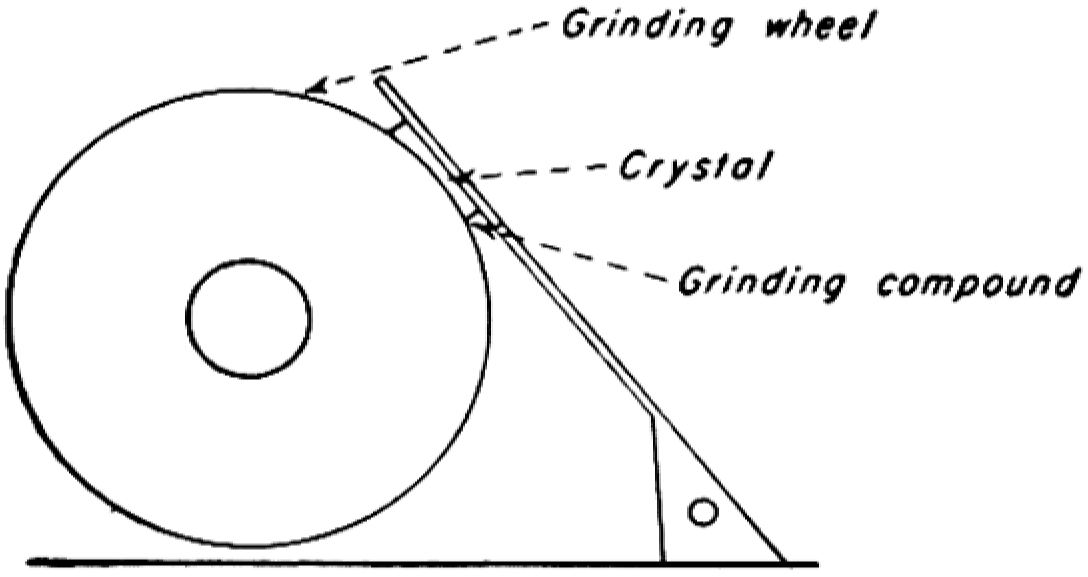


FIG. 3-14. Grinding curved crystals.

Curved crystals should be mounted on curved buttons that match them in diameter. Other than in the amount of curvature, these holders are identical with those described for flat crystals. Curved crystals are usually a little thinner than flat ones used for producing ultrasonic waves of the same frequency.

Crystals cannot be ground to too sharp a curvature without a great loss in activity. The exact amount of curvature possible is a matter of experiment. For test purposes, where the amount of energy is very small, the curvature may be as great as it can be ground.

## CHAPTER IV

## CRYSTAL HOLDERS FOR ULTRASONIC USE

The design of the crystal is, of course, extremely important in order to get the maximum energy and efficiency from the vibrating system, but often the design of a suitable holder or support within which the crystal will perform its function is at least of equal importance. Since most of the design considerations for such holders have been experimentally rather than theoretically determined, a brief résumé of past experience in this field is of interest.

Many of the first holders were planned for submarine signaling and detection. Since a great deal of experiment has been carried out in that field, there is voluminous material in the literature. These types of holders will therefore be most briefly considered, and only general considerations mentioned.

More recently, holders have been designed for test, agitation, and signal purposes. Very little has been published in these fields, and they are accordingly most completely considered.

**Preparing the Crystal.** Prior to its mounting in a holder, the crystal is usually plated, both to make electrical contact with the work and also to distribute the charge more evenly over its surface. This process has already been described.

When the transmission is directly into a solid, both faces are usually plated. If the medium is a conductor, it may be grounded to the instrument by a suitable ground pin or clamp. If it is a nonconductor, however, the front face of the crystal must be returned to the ground side of the electrical system that drives it. It is not absolutely necessary that the front face be plated, and in some cases only the rear one is. However, in the case where the medium does not conduct, a foil or facing must be placed over such crystals and returned to ground.

Once the crystal has been plated and suitable leads connected to one or both faces, it is ready for mounting. These leads may be soldered wires, pins, or springs. It is important, when soldering to a crystal or when contacting it in any way, that the contactor does not damp out vibrations by constraining the natural crystal movement. Usually, a single wire soldered to the center of the rear plating provides all the connection necessary. Spring contacts must be designed so that they do not wear away the plating.

**Holders.** The simplest way to mount a crystal is merely to lay it on the medium into which it is to transmit ultrasonics and to connect the high-voltage end of a radio-frequency generator to its back face. A suitable return circuit is provided by grounding the crystal's front face on the medium itself. This type of mounting works fairly satisfactorily in many cases, but it is awkward to work with and may sometimes be dangerous. It is therefore rarely used. The class of mounting is shown in Fig. 4-1.

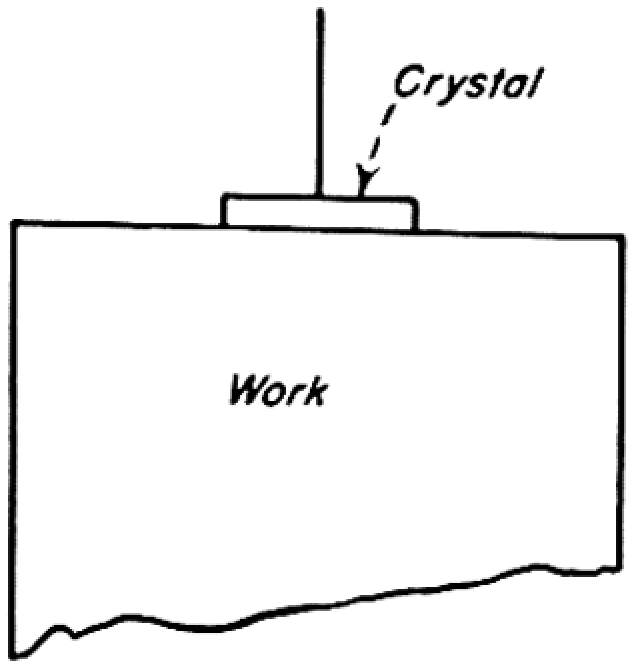


FIG. 4-1. Simple crystal mounting.

However, it is still desirable under certain conditions to have the crystal as free to vibrate as possible. One way of accomplishing this is to support the blank around its sides by pins or knife edges, which barely constrain it. This means of mounting is not very convenient, since it is still difficult to handle the unit. These mountings were originally suggested by Bechmann,[1] who also recommended cutting a groove in the node of the plate for inserting the pins (Fig. 4-2).

The most common type of mounting for signaling or test work at the present time is to fix the back face of the crystal to a solid support of some kind, usually referred to in the case of single crystals as a *button* and in the case of mosaic as a *plate*. This can be done by solder or by a thin film of cement, such as Duco. It is important that all excess cement or solder is squeezed out and removed.

When the crystal is entirely free and supported away from any holder, it will oscillate in a harmonic fashion. However, when it is mounted on a base, it has a tendency to knock against its supports, and oscillations of an uneven character result. This effect is not serious in most ultrasonic work. Investigations of the phenomenon were made by H. Becker in Germany. He also pointed out that a possible shift in the resonance characteristic of the crystal may result from the mounting.

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[1] Bechmann, *Entwicklung der Quarzsteuerung der Telefunken, Grossender, Telefunkenztg,* **14,** Hf. 63, 17 (1934).

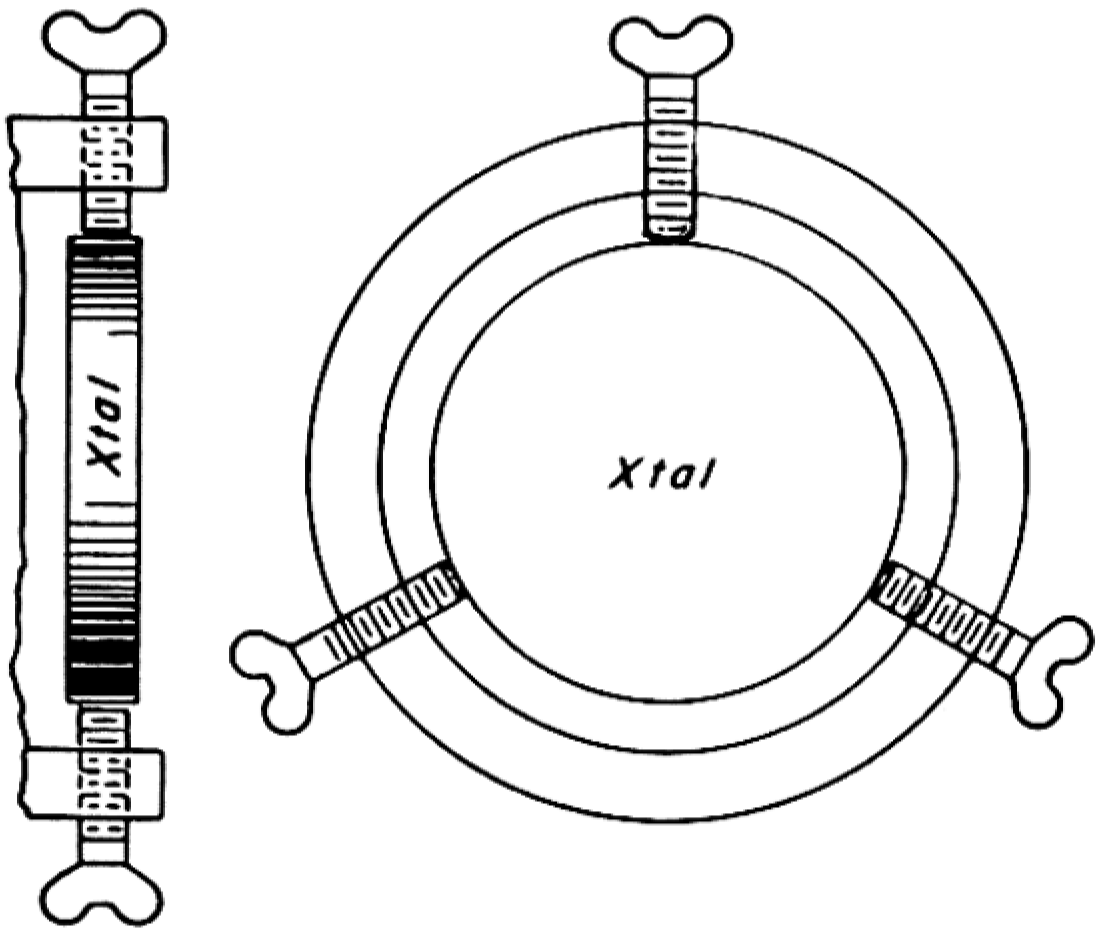


FIG. 4-2. Pin mounting of crystal.

When the crystal is absolutely free, it is almost entirely undamped and might not stop vibrating rapidly enough to be satisfactory in a pulsed or modulated communication system. However, the pressure of the front face of crystal against the medium is generally enough damping to cause free vibrations to die out quickly. On the other hand, when a crystal is very firmly held, the damping may be so great that there is a considerable loss of energy.

In choosing a material on which to mount crystals, it must be remembered that the crystal transmits in both directions perpendicular to its faces and therefore energy may be radiated into the backing. This energy is, of course, wasted and may cause deleterious effects. It should be avoided by backing the crystal with a material of very small ultrasonic transmission such as air, Bakelite, Catalin, or lead. The crystal cannot then send energy into the button. Air will damp the crystal less than the other substances and is therefore preferable. For this reason, when holders are made of solids, it is advisable to relieve the crystal by an air space behind it. Typical buttons used to mount crystals are shown in Fig. 4-3.

In general, crystals will be used for coupling into any of several different media: liquid, solid, or gas. In the case of solids the crystal holder will be held in the hand of the user and slid slowly over the surface of the material under test. For this application the crystal is supported in a holder with one face protruding so that it can be applied more easily to a surface. In the case of liquids or gases the crystal may be supported in any one of a number of ways. One surface must, however, be in contact with the medium, and the other returned to the hot side of the generator. The front facing is connected to ground.

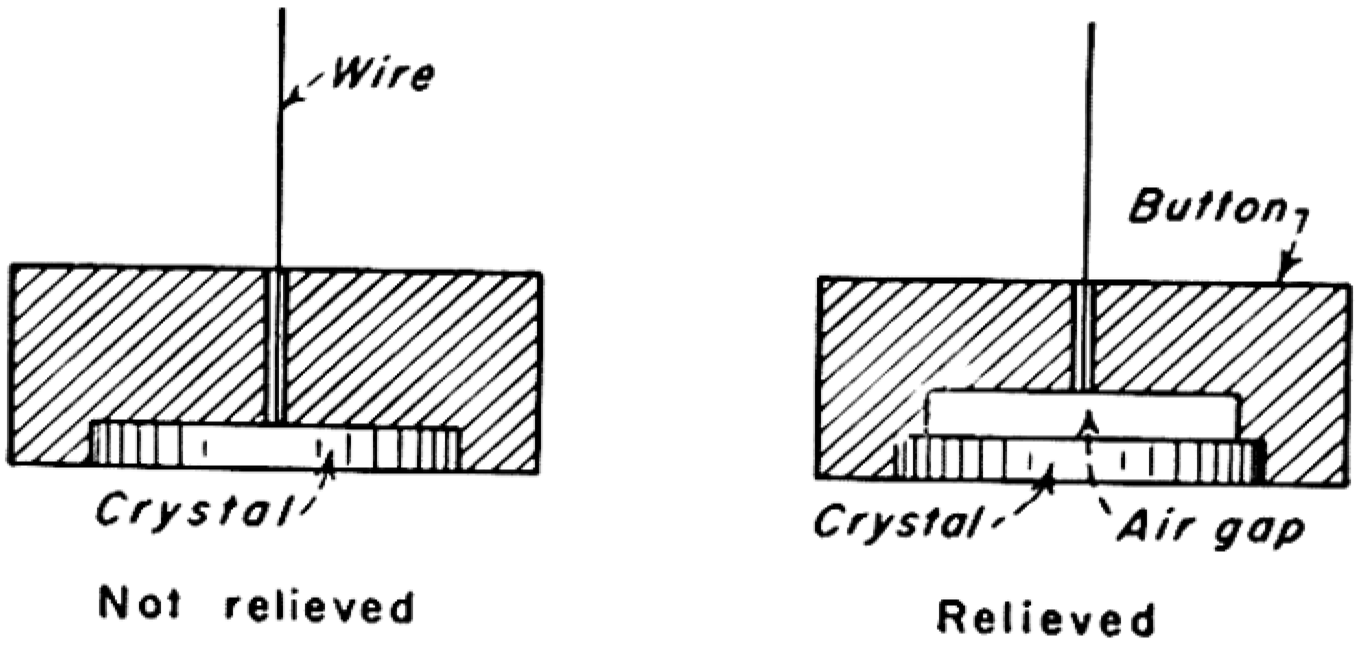


FIG. 4-3. Typical buttons for crystal support.

The crystal is either free or clamped at its rear face. These mountings are referred to as *clamped* or *inertia drive*. The latter is the more commonly used. The mathematical derivations and equivalent circuits have been discussed in the literature.

Crystals can be mounted singly stacked, or in mosaics for greater output and area coverage.

In test and signaling work it is generally desirable to get as much power as possible into a short sharp pulse if the pulsed type of signal is used. In continuous-wave work the holder should always be designed for maximum transfer of power and minimum damping. In pulsed and modulated methods power must be sacrificed, since it is also necessary that the time constant of the crystal, *i.e.*, its time of free vibration after the signal is removed, be less than that of the signal; otherwise it will not follow faithfully. Therefore, damping may actually be added.

**The Holder for Impressing Ultrasonics on Solids: Longitudinal Waves.** The function of the holder in generating ultrasonics is to support the crystal firmly with its front face far enough advanced so that it makes excellent contact with the material. It should also provide a minimum of damping on the rear face and on the sides so that the crystal can vibrate freely. A protrusion of approximately 0.005 in. is sufficient. The holder must also include a suitable means for grounding the plated face of the crystal and for connecting the high-frequency electrical energy to it without danger of injury to the operators. It must be light and easily held and preferably of a size and shape that will fit into small openings where testing is to be done or signals impressed. The crystal should occupy the major part of the front face, which should be designed so that the edge of the crystal is near at least one of the edges of the face. This enables the operator to bring the crystal up against fillets or ledges. Figure 4-4 shows common holders used for this purpose.

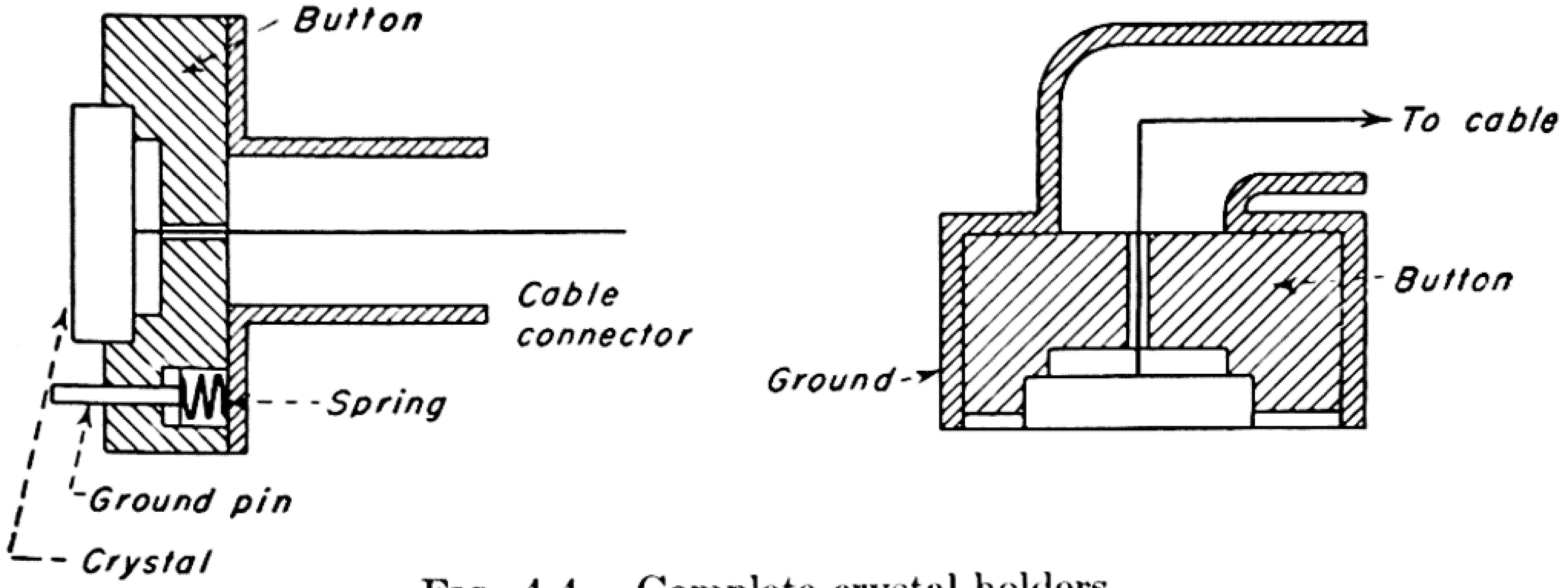


FIG. 4-4. Complete crystal holders.

The holder is merely a support for the button. It may be either straight or bent at any angle. In any case it will usually include a piece of tubing that supports a connector into which a cable can be plugged. Sometimes, it is merely a sleeve through which the cable runs. The design of the holder is purely a mechanical one, and there are no real problems associated with it.

**The Button.** As indicated, the crystal is mounted on a backing referred to as a button. The design of this button is of the greatest importance, since it is the item that actually controls the ultrasonic activity of the crystal.

Buttons for test and signal purposes are usually fairly simple and consist of a piece of material that is ultrasonically nonconducting and into which the crystal fits. The crystal is supported about its edges and so mounted that it is constrained a minimum amount. A cutback or shoulder is provided as shown in the illustrations. The crystal is cemented into the button with de Khotinsky or similar cement.

The crystal should fit snugly into the button cutbacks and should be supported in such a way that it does not knock against them. The button should be of material that will not absorb oil or other liquids in which it is operated.

Certain of the following topics relate to specific problems of button design.

**Air-gap Resonance.** Although it is true that ultrasonic propagation in air is heavily damped in a very short distance, it is still possible for air-gap resonance to occur. This term refers to the action that takes place when a crystal is mounted on a button with the back relieved, *i.e.*, with a cutback behind it so that it is supported away from the backing by an air gap. In such a case an ultrasonic wave may travel away from the rear of the crystal through the very small air gap, hit the back wall of the holder, and be reflected back to the crystal. If the total distance traveled compares in certain ways with the ultrasonic wavelength, interferences may occur. These interferences may either aid or damp the ultrasonic vibration of the quartz, depending upon the specific dimensions.

The velocity of ultrasonics in air is about 1,100 ft/sec. Since the air gap is resonant at one-half the wavelength, the dimensions of a resonant gap differ with the wavelength and can be calculated for any one frequency.

$$\lambda = \frac{c}{f}$$

where $\lambda$ = wavelength
$c$ = velocity
$f$ = frequency

Therefore the gap, which equals $\frac{1}{2}\lambda$ for resonance

$$\frac{\lambda}{2} = \frac{1}{2}\frac{c}{f}$$

A common ultrasonic test frequency is 5 mc. At this frequency

$$\frac{\lambda}{2} = \frac{1}{2}\,\frac{1{,}100 \times 12}{5 \times 10^6}\,\frac{\text{(in.)}}{\text{cycles}}$$

$$\frac{\lambda}{2} = 0.0013 \text{ in.}$$

Of course, the effect will cause interference only in the case of generators of $L$ waves, *i.e.*, $X$-cut crystals.

Physically, the action can be explained as follows. At the moment that the crystal is fully flexed in one direction, a pulse of air starts toward the reflecting surface, hits it, and returns to the crystal. However, the crystal has vibrated in the other direction and is now returning to its starting position. The pulse of air will therefore interfere with its movement, tending to prevent the blank from vibrating as freely as it normally would. If the action of the crystal is to be reinforced, gaps of ¼ λ would be indicated.

In those cases where signal reinforcement is not desired, it is preferable to avoid air-gap resonances. Almost all ultrasonic buttons are designed in this manner. In any case, the distances involved are so small, because of the velocity of travel, that it is extremely difficult to hold design tolerances in terms of fractions of wavelengths.

**Crystal Damping.** It is necessary for the crystal to follow rapid variations not only in order to follow the oscillations themselves but also in order to reproduce the modulation on the electrical or ultrasonic signal. For example, in the use of a crystal with a pulsed ultrasonic system, the crystal should stop oscillating abruptly at the end of a pulse. Otherwise, the original form of the signal is obscured. In order to accomplish this, some loading or damping of the crystal may be necessary. Usually, this damping should be as slight as possible and never more than is absolutely necessary, since it makes the system more inefficient.

However, attempts have been made to fix a mass or load to the back of the crystal in order to damp out any free ringing in the system. Such a system is disclosed in U.S. Patent 2,398,701[1] and is shown in Fig. 4-5. A material that does not conduct ultrasonically is fastened to the back of the crystal, and a greater band width results, together with a damping of free oscillations. Such systems have the disadvantage that there is a loss in the general amplitude of oscillation and therefore in the over-all sensitivity.

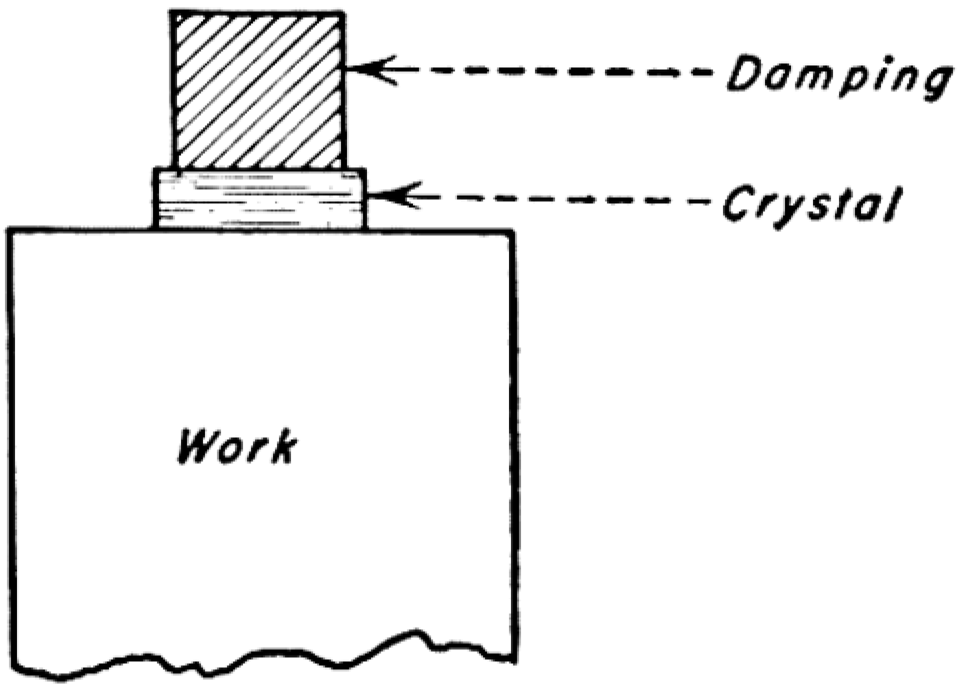


FIG. 4-5. Damping the crystal.

The amount of damping is determined experimentally. Figure 4-6 shows crystals held in buttons in each of which a different area is impressed on the back of the crystal. There is therefore a different damping on each.

These systems may be thought of as varying the band width of the crystals by mechanical means. As the damping becomes greater, the band width also increases. Damping is sometimes referred to as *dampening*.

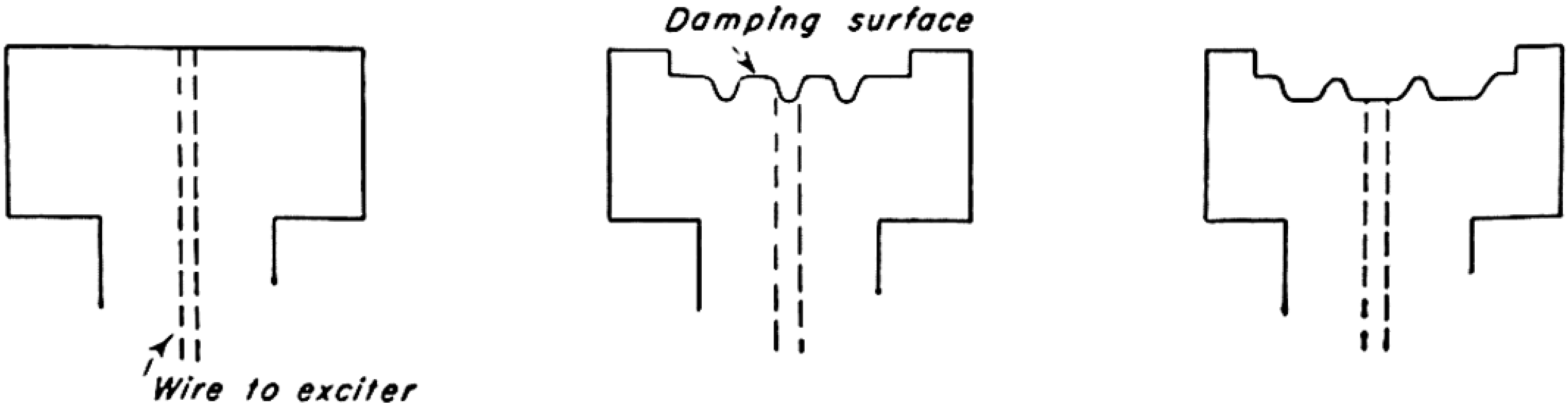


FIG. 4-6. Buttons with different damping effects.

It has already been mentioned that the amount of damping on the crystal can be controlled (at least as far as addition is concerned) by the method of mounting. Generally, the crystal is sensitive to the material to which it is mounted; and if it is firmly held by its backing, the amount of damping will vary approximately with the area of cross section that is fastened to the backing and/or comes into intimate contact with it. Thus, if a crystal is held only about its edges and nowhere else touches

[1] F. A. Firestone, April 16, 1946.

the back, the damping is minimum; while if the whole area is held firmly, the damping is maximum.

The design of buttons for damping the crystal may be inferred from what has already been said. In each case different amounts are brought into contact with the crystal and cemented firmly.

**Standoffs.** In testing materials the flaw sometimes falls so close to the test or sending surface that the reflections fall within the body of the transmitted pulse. It is theoretically possible to separate such signals from the pulse by means of either an electrical or mechanical delay between the transmitted pulse and its reflections (Fig. 4-7).

**Mechanical.** A mechanical piece used for this purpose should be long enough to separate the pulse and reflections clearly. Otherwise, secondary reflections from the interface between the standoff and the work may confuse the signals. The diameter of the standoff must be large enough so that waves crossing it and reflecting from the sides will not return during the pulse-signal duration. The sides may also be sintered or corrugated to prevent these reflections.

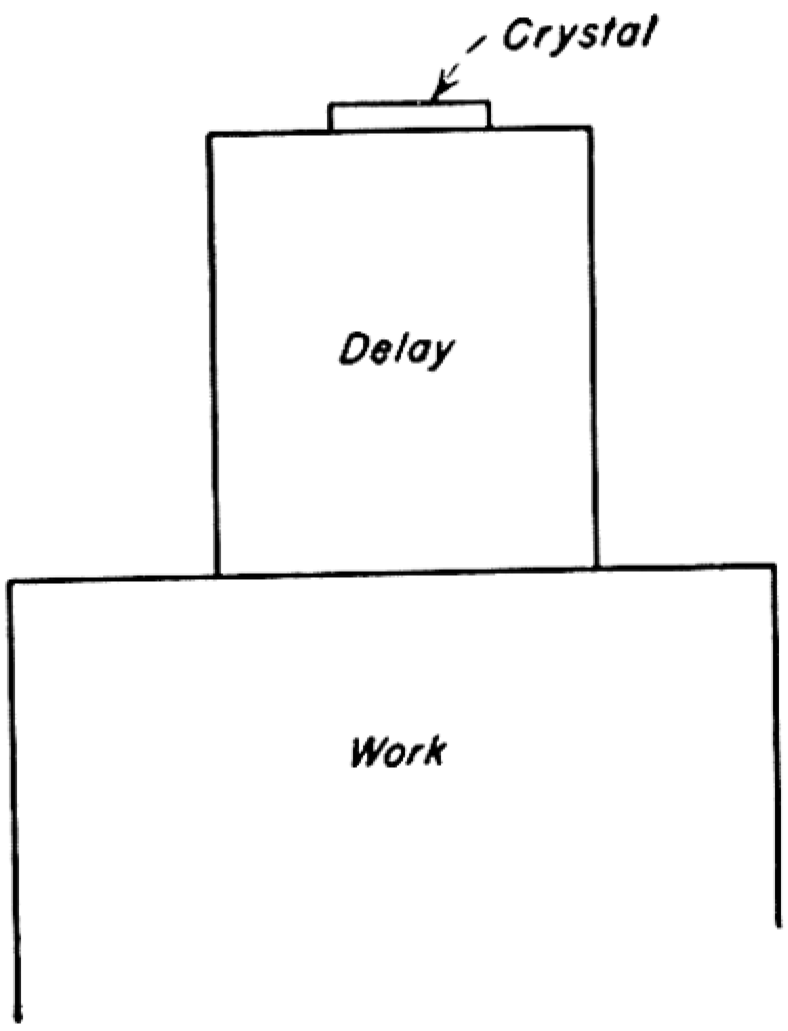
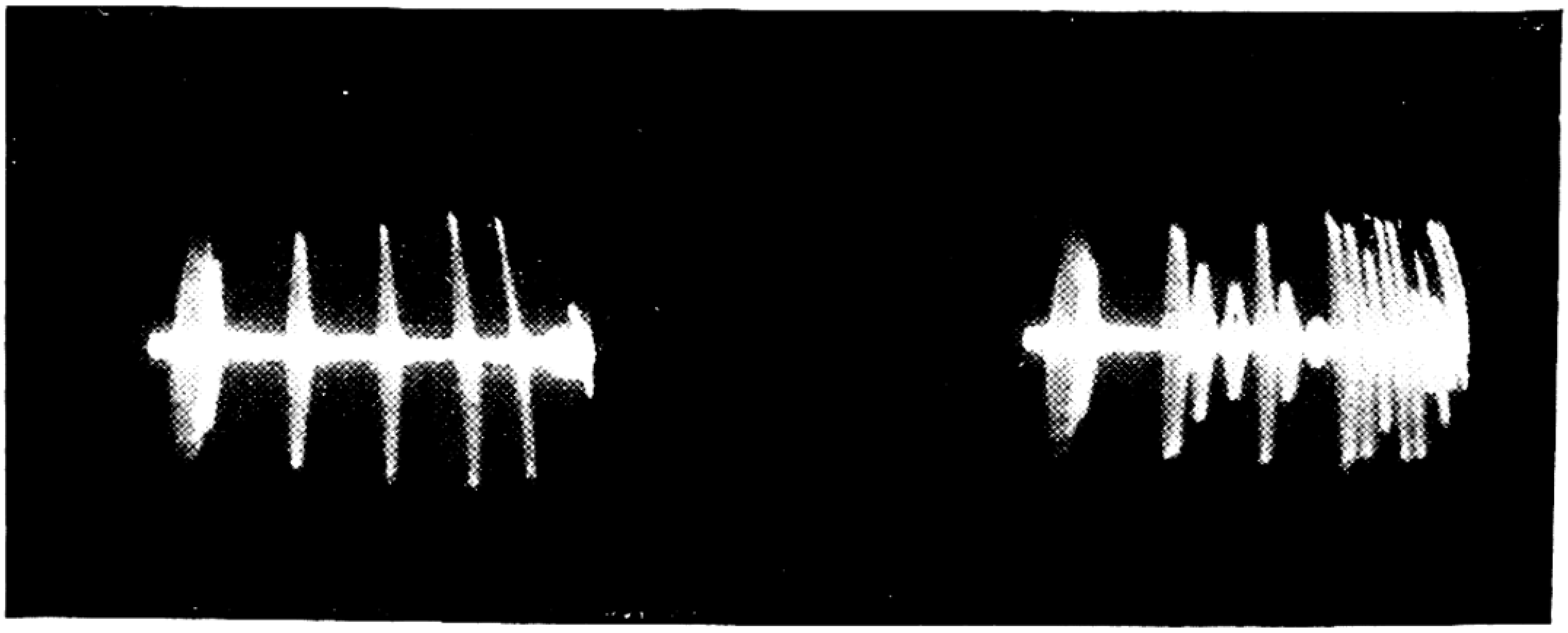


FIG. 4-7. Mechanical delay.

The use of mechanical standoffs of metal for delaying ultrasonic signals has not been very successful because of the internal reflections and the large reflections at the interface.

If no method of separating reflections from the transmitted pulse is used, there is always a minimum distance over which signals can be detected separately; *i.e.*, if a signal only travels for 1/100 μsec and is reflected, it will return so quickly that it is confused with the original transmitted signals. Without special means of delay such as those indicated, the minimum distance that can be easily measured by the echo technique is about ½ in. of steel, *i.e.*, about 4 μsec. However, by special techniques, signals only a fraction of a microsecond away can sometimes be detected.

During the late war, standoffs were used to provide delays in ultrasonic echo boxes used in Germany as radar setup devices. In these units the pulse traveled through a piece of material and was reflected and received back after a time interval comparable to those intrinsic to the radar system when actually operating, thus providing a calibrating pulse. Figure 4-8 shows signals provided by mechanical standoffs.



(*a*) (*b*)

FIG. 4-8. Signals from mechanical delays: (*a*) delay line only, (*b*) delay plus additional signal.

**Fillers.** Where the surface of the medium is slightly curved, either in a convex or concave direction, it is sometimes expensive or impractical to grind the crystal itself to fit the curvature. In order to make contact, a filler may be inserted in the space between the crystal and the work. Any material can be used for a filler, but the closer its acoustic impedance is to that of the crystal the more efficient the results will be. Since aluminum or duraluminum has an acoustic impedance of $1.68 \times 10^6$ while quartz has one of $1.52 \times 10^6$, there is excellent match between the two materials, and duraluminum is therefore used for fillers. Because of the excellent impedance match, there is a minimum of refraction and reflection.[1] Duraluminum shows less wear and friction than aluminum and is therefore preferable.

Fillers of about 0.050 in. are most satisfactory. As the filler becomes thinner, more energy is transmitted through it but the signal clarity deteriorates. When the filler gets much thicker, there is a strong loss of energy. Figure 4-9 shows the location of a filler between the crystal and the work for both concave and convex curvature.

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[1] F. W. Struthers, Supersonic Measurement of Wall thickness in Diesel Liners, *Naval Research Rep.* S-2932.

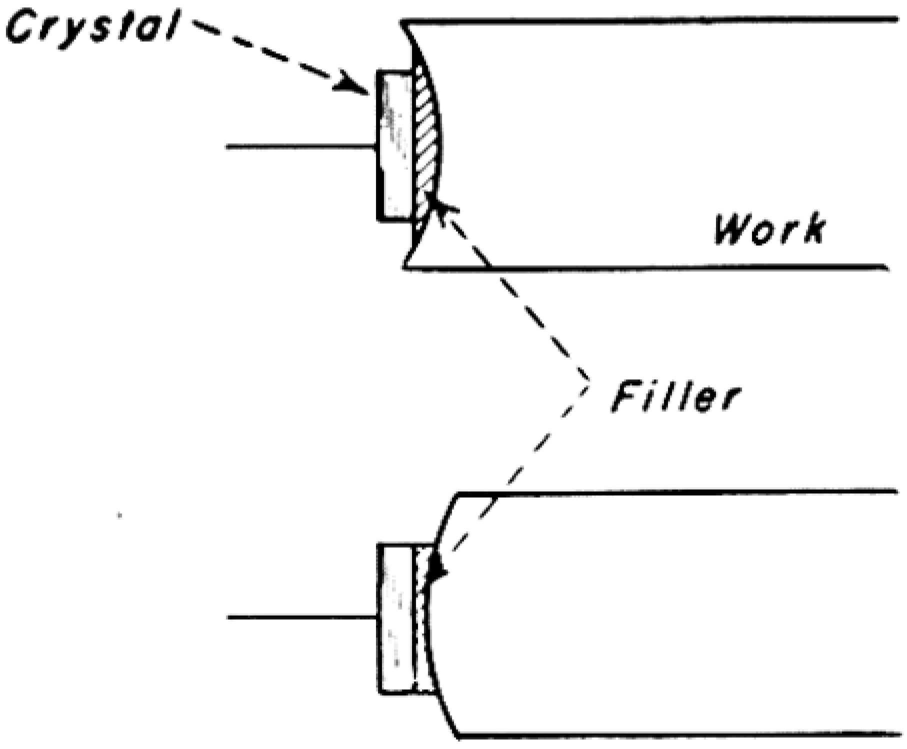

FIG. 4-9. Location of fillers.

Liquid fillers can also be used but are not practical because the liquid escapes and must be constantly replenished. Mercury or heavy oils are suitable.

**Spring Mountings.** It is sometimes necessary to hold the crystal a fixed distance from the medium, while at the same time moving one with respect to the other. This can be accomplished by spring mounting the crystal so that it is positioned before the work by some sort of gauging device. A desirable feature of spring mount is that the crystal is always held at the same specific pressure.

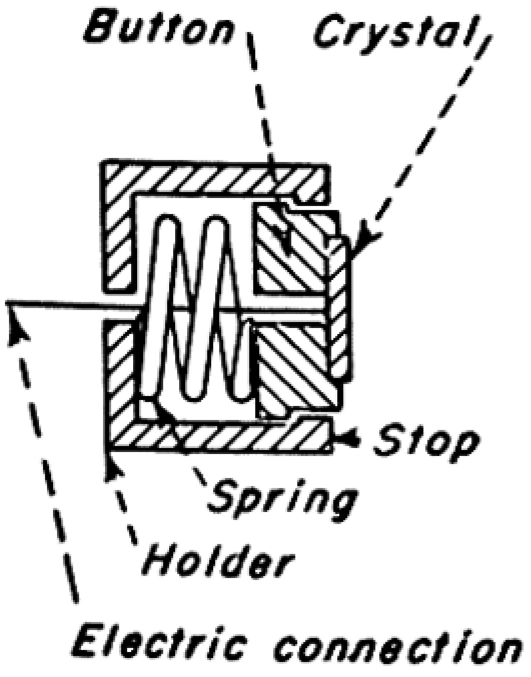

FIG. 4-10. Spring crystal holder.

Spring mounting is especially important for the crystal when it is hand held, since variations in pressure will cause variations in the signal strength. A unit that can be used for this purpose is shown in Fig. 4-10. The high-frequency voltage may be impressed upon the crystal either by the spring itself or by a separate lead. The crystal may be sprung within the holder, or the entire holder may be sprung within an external casing. When the button is sprung, it should also be keyed so that it will not turn. Rotation of the unit results in damage to plating and crystal.

Moreover, in cases where it is desirable for the receiver head itself to follow variations in the contours of a part and rest upon the part, the crystal can be placed in a flexible head, such as the one in Fig. 4-11. A diaphragm, either of rubber or a similar material, allows limited movement of the crystal so that it is always pressed to the part no matter what the contour. This system was first suggested by Shraiber, who used it to test curved surfaces. Rubber is attacked by oil, so synthetic substitutes are preferable.

The design of spring mountings is obvious, and mechanical considerations predominate. However, care must be taken that the button or other spring member does not bind as it progresses over the work, since erratic indications will then result. The spring must not touch the case or other metal parts of the unit. A minimum spring pressure is preferable.

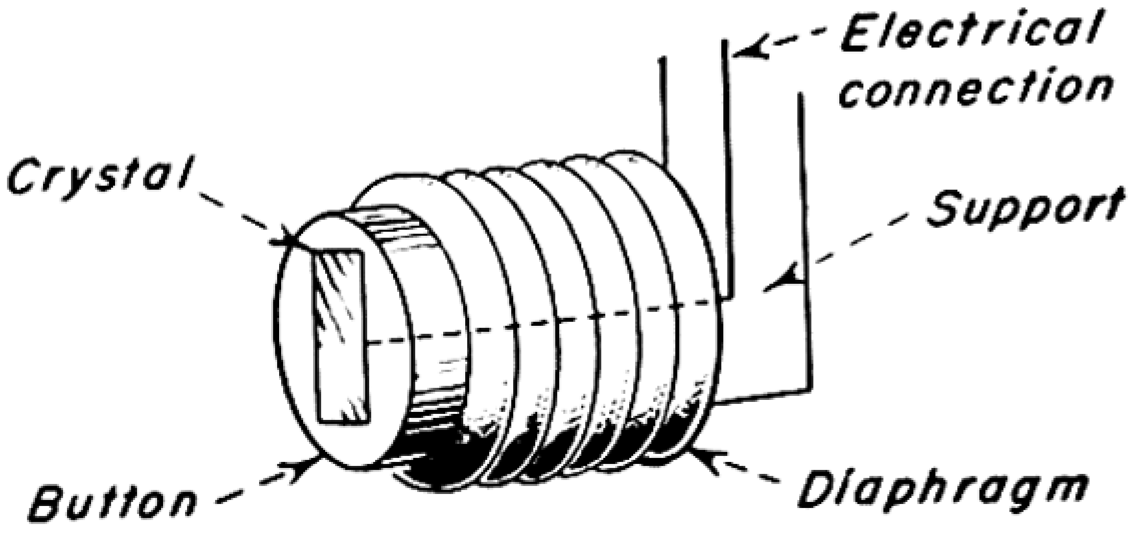

FIG. 4-11. Flexible holder.

**Magnetic Holders.** When working with materials that have magnetic properties, a magnetic shell may be placed around the transducer or its shell magnetized so that it will adhere to the work. This is sometimes convenient, since it helps support the crystal and frees the operator's hands.

When magnetic holders are used, the crystal button must be sprung, since otherwise it will not make good contact with the work.

**Holders for Angular Propagation.** It is sometimes advisable to transmit energy into a material at an angle, and holders for this purpose can be constructed. An angular wedge of material of the same nature as the medium is fastened to the front of the crystal. Since the material is the same and since there is a very thin film of oil between it and the medium of travel, there will be essentially no refraction at the interface but the waves will travel directly through into the material in a straight line. There will be no transformation of ultrasonic energy at the interface.

Holders for this purpose have been constructed and used here and in Great Britain and are well known in the art. However, they are not suitable for use with the reflective technique, since there is a great deal of reflection at the interface. If the system is set up to measure the time of travel of a pulse, there will be so much interference because of spurious signals returning from the interface that the real signal cannot be distinguished from them. Ultrasonics have also been transmitted into a material at an angle through a liquid in Germany.

When angular transmission is used, it is advisable to have a separate pickup crystal, which also operates at an angle and which receives the energy reflected from the obstacle that it is desired to locate.

Suitable angles for such use are about 30 deg. In the case of liquid couplers, mercury or a liquid of acoustic impedance matching that of the work should be used; otherwise reverberations, *i.e.*, build-up of reflections within the liquid, will occur. Figure 4-12 shows the placement of angular holders.

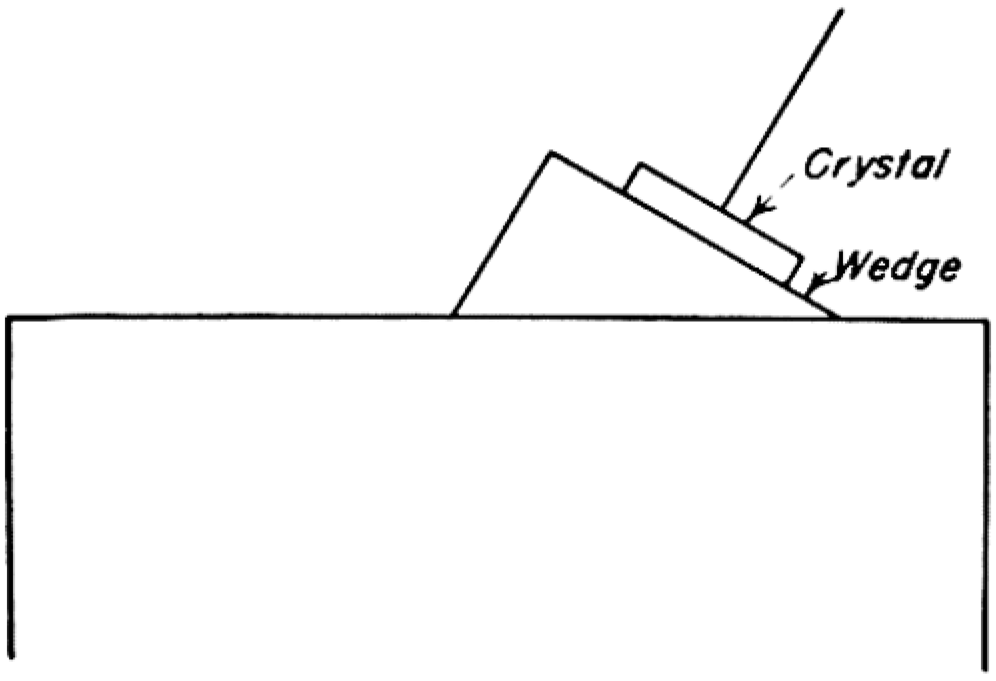

FIG. 4-12. The angular holder.

Angles of a material other than the medium may also be used. In that case transformation of waves and refraction both occur. The angles are designed according to the theory of wave transformation, so that only $S$ waves are propagated in the material. Under such conditions there is little reflection at the interface, and accordingly the unit can be used for pulsed reflective applications.

**Holders for Transmitting through Liquids into Solids.** Another method of coupling the crystal to the medium is to transmit waves through a small amount of liquid trapped in a container. Such a system is shown in the German Patent 654,673 of Dec. 24, 1937, in which a crystal is supported in a bath in such a way that the energy from it can be focused at some point inside a solid material on which the liquid rests. In this particular case a curved crystal is used. The liquid is kept within the holder by a diaphragm that fits tightly around its bottom and against the medium into which the waves are to be transmitted. Provision is made for continuously adding liquid to the holder. A well or trap may be included to maintain the liquid level.

This type of holder is useful where the surface of the material is very rough or where the contour of the crystal is such that it will not fit directly against the material. The chief disadvantages are its messiness and the difficulty of continuously moving the holder without losing the liquid. Suitable liquids for inclusion are any of those which will transmit ultrasonic vibrations. Of these, mercury is the most suitable, but it is both dangerous and hard to see.

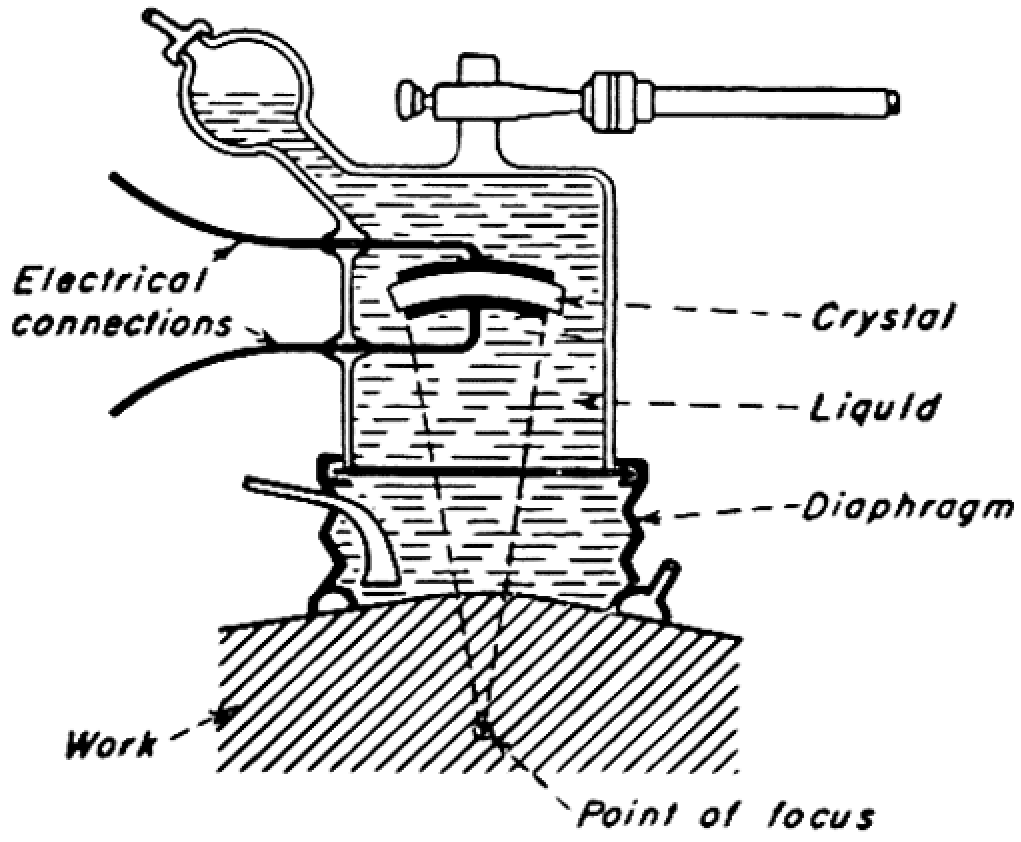

FIG. 4-13. Holder for transmitting through a liquid into a solid.

The liquid-containing holder has never had very widespread use and is not as yet practical for reasons already indicated. It is obviously capable of variations. The disclosure for the German patent is shown in Fig. 4-13.

**Holders for Shear or Surface Waves in Solids.** Shear and surface waves can exist only in solids, since there is no shear modulus in liquids or gases. A holder for shear-wave crystals should leave free the two ends of the blank that are perpendicular to the direction of shear vibration. If those ends are closely clamped, the vibration of the crystal will be stopped. The buttons are, therefore, constructed in a manner that closely resembles the longitudinal wave button except that the two ends are open. The same button can be used for both surface and shear waves except that in the case of surface waves it is usually much longer, and thinner than in the case of shear waves.

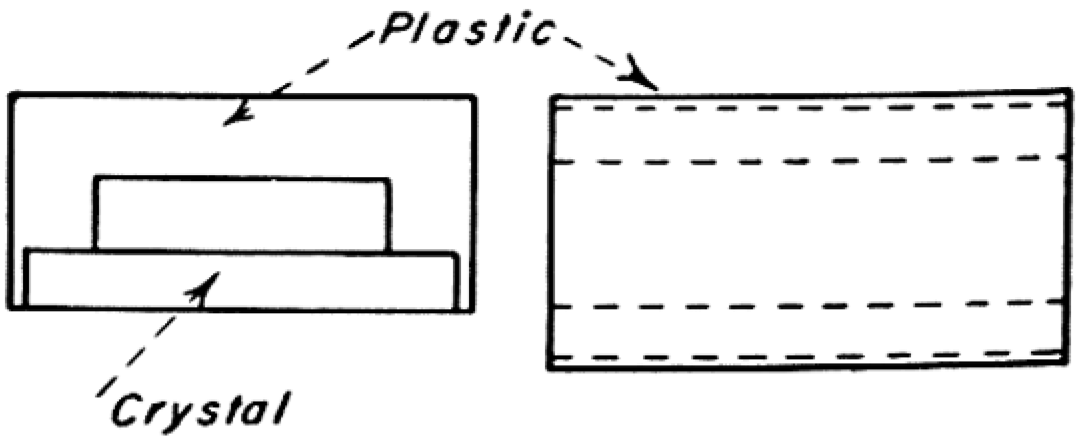

FIG. 4-14. Surface-wave holder.

Surface waves can sometimes be propagated in only one direction by tilting the crystal slightly. The waves will then travel away from the edge that is against the medium. A surface-wave holder is shown in Fig. 4-14.

Rayleigh- or surface-wave crystal design criteria have already been discussed. Obviously the button must be designed to fit such crystals.

**Support in the Liquid.** The testing of parts immersed in a liquid has been a common ultrasonic approach in the past that has certain basic advantages. The parts under test can be continuously moved between the transducers. In such cases special holders must be designed for the crystals, and in general the holder shape is not important, but it must be waterproof and convenient to use. The crystal may be held either perpendicular to the axis of the holder or parallel to it, and the function of the holder is essentially to protect the electrical connections from the liquid and to hold the crystal rigidly. The ultrasonic beams generated in a liquid may be either horizontal or vertical in direction, but the holders should be far enough removed from the surface of the liquid so that troublesome reflections do not occur. Moreover, screens can be placed within the tank either to absorb energy or to protect the holders from stray beams that are reflected back and forth in the liquid. The method of supporting buttons in holders for liquid use is shown in Fig. 4-15.

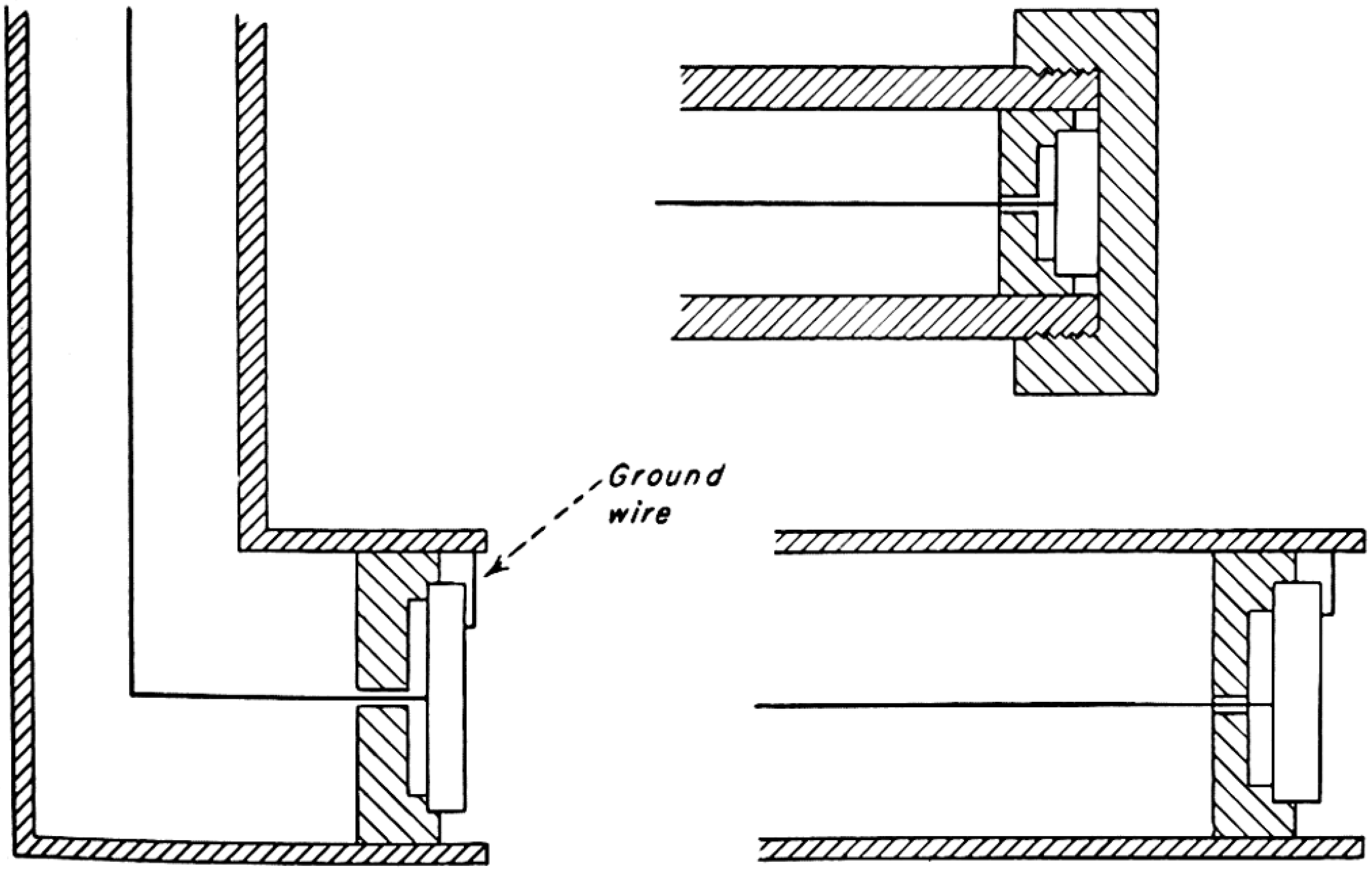

FIG. 4-15. Holders for use in a liquid.

In certain cases the crystal can be fixed directly to the wall of a tank and radiate through a hole in it. Such an arrangement is indicated in Fig. 4-16. However, this system has the great disadvantage that it is not sufficiently flexible. For example, in such a case, when it is necessary to change the frequency of operation, a new tank must be used. For that and other reasons holders of the type shown in Fig. 4-15 are preferable to those described above.

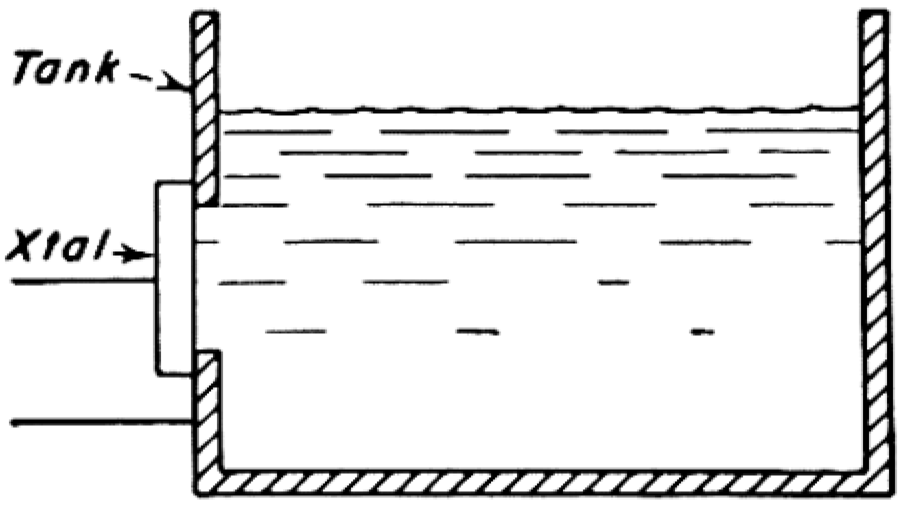

FIG. 4-16. Crystal and tank as a unit.

**Beam Interrupter.** It is occasionally desirable to interrupt a beam of ultrasonic vibrations that is traveling through a liquid bath. A beam interrupter (Fig. 4-17) can be made that will perform this function. The device consists of a plate that can be interposed in the ultrasonic beam and will not allow the energy to be transmitted through it. Since the reflection from an air-metal interface is practically 100 per cent, the simplest type of interrupter is formed of two sheets of metal or other material between which there is a small air pocket. Sometimes a sheet of material that does not transmit ultrasonics may be included in the air space. Bakelite or a similar plastic can be used. An interrupter should be furnished with a handle by which it can be manipulated.

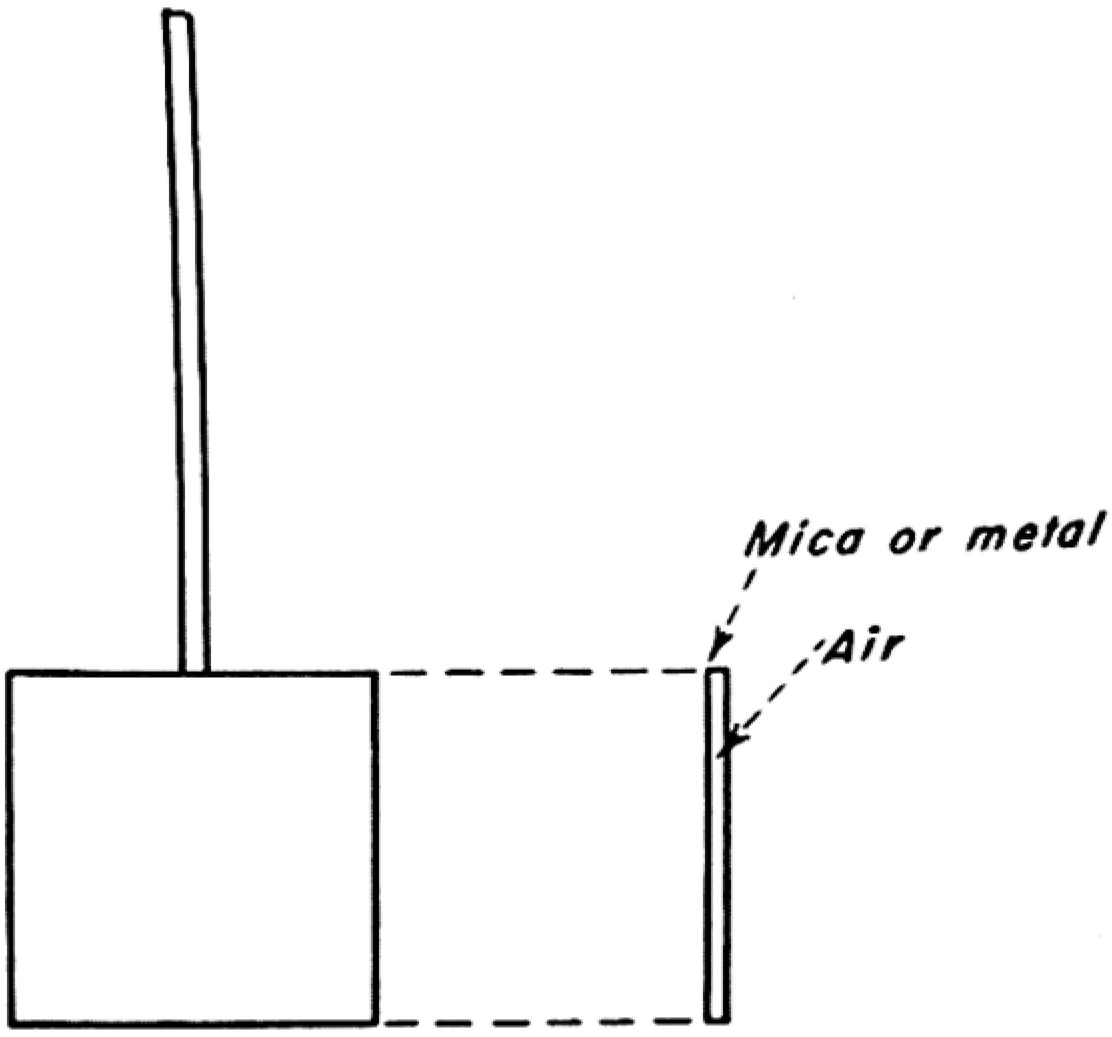

FIG. 4-17. The beam interrupter.

The design of a beam interrupter is therefore essentially the same as that of the reflecting plate of a torsion balance.

The beam interrupter is used as a means of checking indications that occur when working in a liquid. In such a case it is difficult to say whether a specific signal indication results from an ultrasonic wave or not. However, when the interrupter is interposed in the energy stream, the signal disappears when it is an ultrasonic one. If the indication were an electrical one, the placement of the interrupter would not influence it.

**Tanks.** Most through transmission systems operate effectively when used in conjunction with a tank containing liquid in which the articles under test are immersed. The liquid acts as the coupling agent and may be oil, water, etc. It also allows the continuous passage of the material between the two transducers. A tank system is shown in Fig. 4-18.

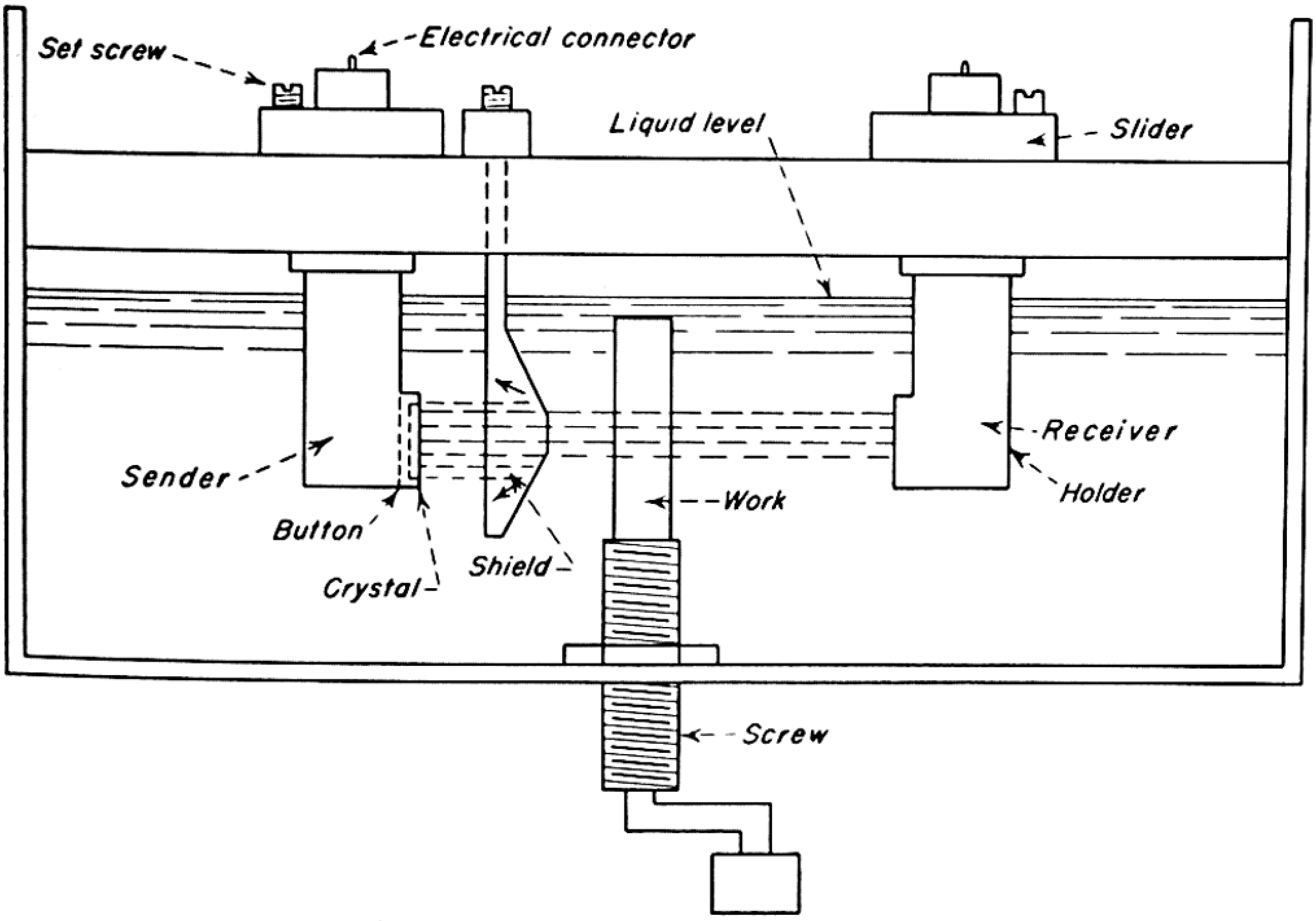

FIG. 4-18. Complete tank system.

Naturally, some means of moving the material must be provided. This may take the form of rollers or a screw mechanism. Any part of the setup that is to be touched by the operator must be grounded and preferably insulated.

The transducers are normally mounted on railings such as those shown in Fig. 4-18 and may be slid back and forth so that their positions can be conveniently adjusted.

The tank should be large enough so that there is very little reflection either from its sides or bottom or from the surface of the liquid. The crystal must, therefore, be deep enough under the surface so that ultrasonic energy, due to spreading or scattering of the beam, does not reach the liquid surface.

Wetting agents, such as aerosol, will prevent the formation of bubbles on the transducer faces.

Waves or currents in the liquid can be prevented by screens or baffles. Materials such as Cellophane will prevent currents without interfering with the passage of ultrasonics.

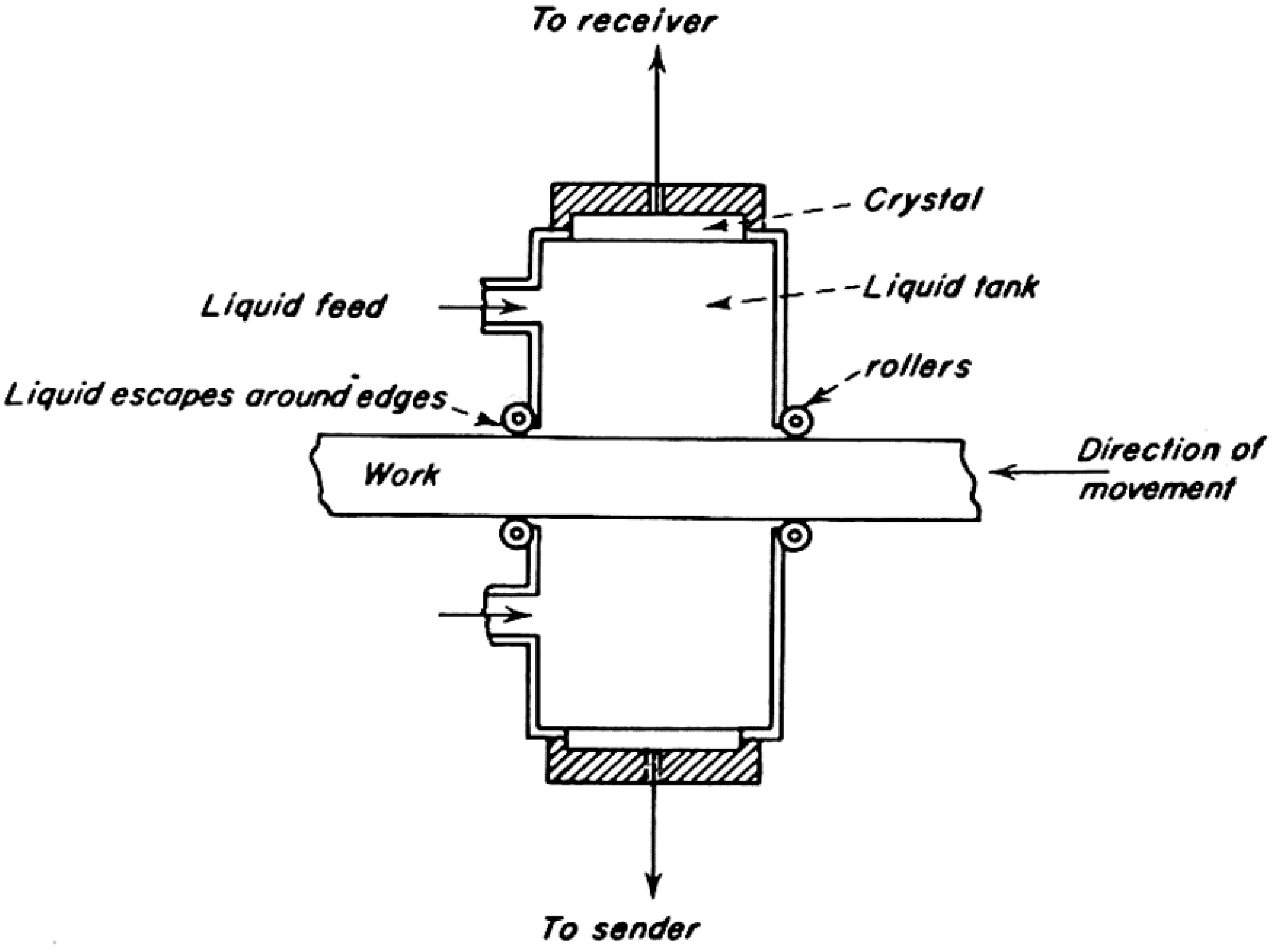

FIG. 4-19. Method of maintaining liquid contact to a part.

Means for filling and emptying the tank easily should be provided. Temperature-control devices and immersion thermometers are also useful. However, close control of experimental factors is not necessary for most applications other than laboratory ones.

An entire system for testing in a tank is shown in Fig. 4-18. Sending and receiving crystals are mounted in the L-shaped holders. The path of the ultrasonic beam is indicated by the dotted lines. A shield is provided for limiting the cross section of the beam. The work is supported in the path of the beam on a turntable on which it can be rotated and concurrently raised or lowered. The entire mechanism operates on a slide on which it can be moved about. This type of system seems to have been originally used by Shraiber.

A tank is not always necessary, even though the medium is to be tested in a liquid. Liquid may be led to the holders through pipes, as in Fig. 4-19. The crystal is spaced away from the work, but a constant ultrasonic contact is maintained by the flow of liquid. In this particular case the holders are equipped with rollers, which maintain a fixed distance between the crystals and the work. The units may be moved in unison over the face of the work. This type of equipment was originally used in Germany.

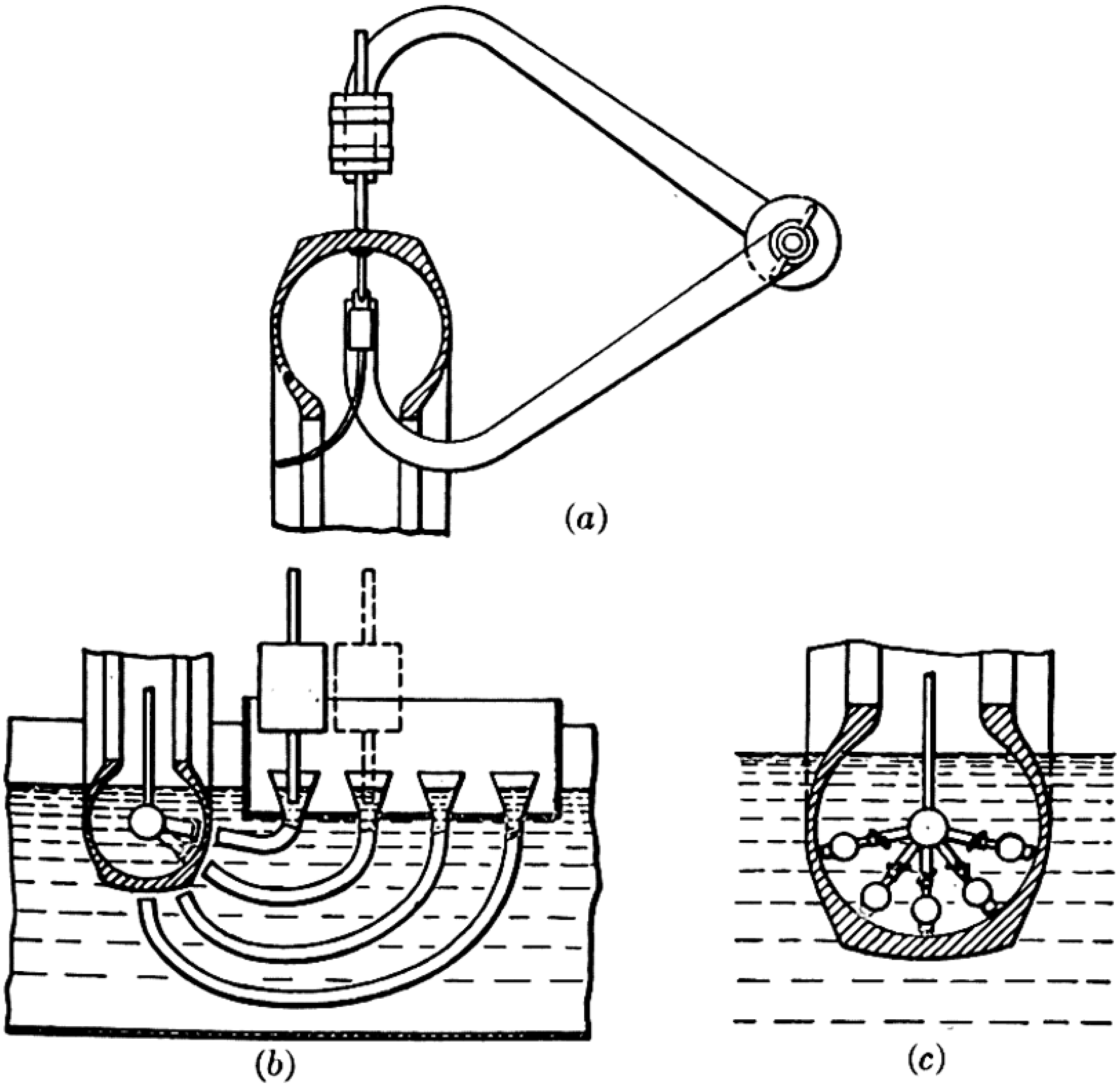

FIG. 4-20. Alternate search unit positions for operating in liquids.

A combination of such systems for testing tires ultrasonically is shown in Fig. 4-20.[1] Various ways of positioning the search units will become obvious from a study of the figure, which illustrates a number of possible combinations.

**Beam-limiting Devices.** In certain cases the divergence of the beam may be too great for use. In others waves may be produced that travel in directions other than that desired, and their production may be unavoidable. Such waves cause troublesome reflective effects, which obscure the test or signal results to an appreciable degree. Some of these waves may be produced by the back face of the crystal, and in that case absorptive material may be fastened where it will absorb them without interfering with the motion of the crystal. Holders of this sort may also be used in liquid transmission systems, where the setup is more or less such as that shown in Fig. 4-18. In this case it is desired to test for very small flaws in the work, and the beam is appreciably greater than the size of the flaws. As a result some of the energy will pass around the flaw and travel through the good material that surrounds it. Since the principle of operation is that the flaw must interrupt the energy in the beam, the whole mechanism is inoperative under such conditions. Limiting devices such as Fig. 4-21[1] are therefore used, in which the aperture is about as large as the smallest flaw it is desired to find. The beam is therefore limited, and the excess portions either absorbed by the baffle or reflected in such a manner that it is not harmful. For this purpose the inside of the baffle may be corrugated to break up the beam or fitted with absorbent material.

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[1] W. E. Morris, U.S. Patent 2,378,237.

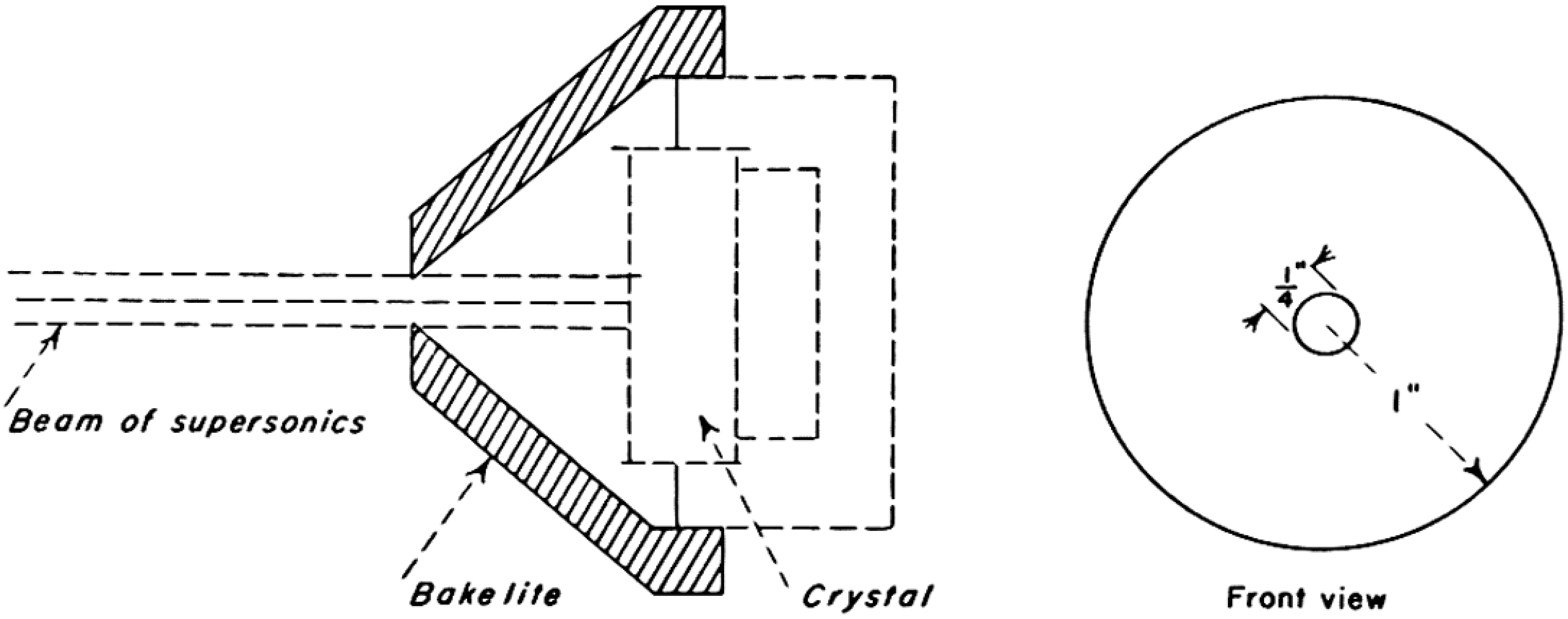

FIG. 4-21. Beam-limiting device.

The baffle may also take the form of a sheet of ultrasonically nonconductive material held perpendicular or at any angle to the ultrasonic beam or may be formed of two pieces at angles to each other (Fig. 4-22). A number of combinations is possible, but the basic principle is the same. In each case a small hole is drilled to allow energy of the same cross section to pass through.

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[1] B. Carlin, U.S. Patent 2,448,352, Aug. 31, 1948.

**Further Considerations in Solids.** *Coupling the Crystal to the Work.* If a crystal is placed on the surface of a dry part, very little energy will be transmitted through the interface into the material because of the great difference in specific acoustic impedance at the interface. It is therefore important that some kind of coupling medium be used. This coupling may be looked upon as a transformer, which matches the impedance of the crystal to that of the work. It therefore preferably takes the form of a liquid whose specific acoustic impedance is somewhere between that of the quartz and that of the material. Probably the most satisfactory material for this purpose would be mercury if this were the only consideration. However, it is both expensive and dangerous. Luckily the particular couplant is not critical, and various oils have become popular, the most common of which is a nonconducting transformer oil such as Wenco. Glycerin gets slightly more energy into a metal part but is messy and hard to

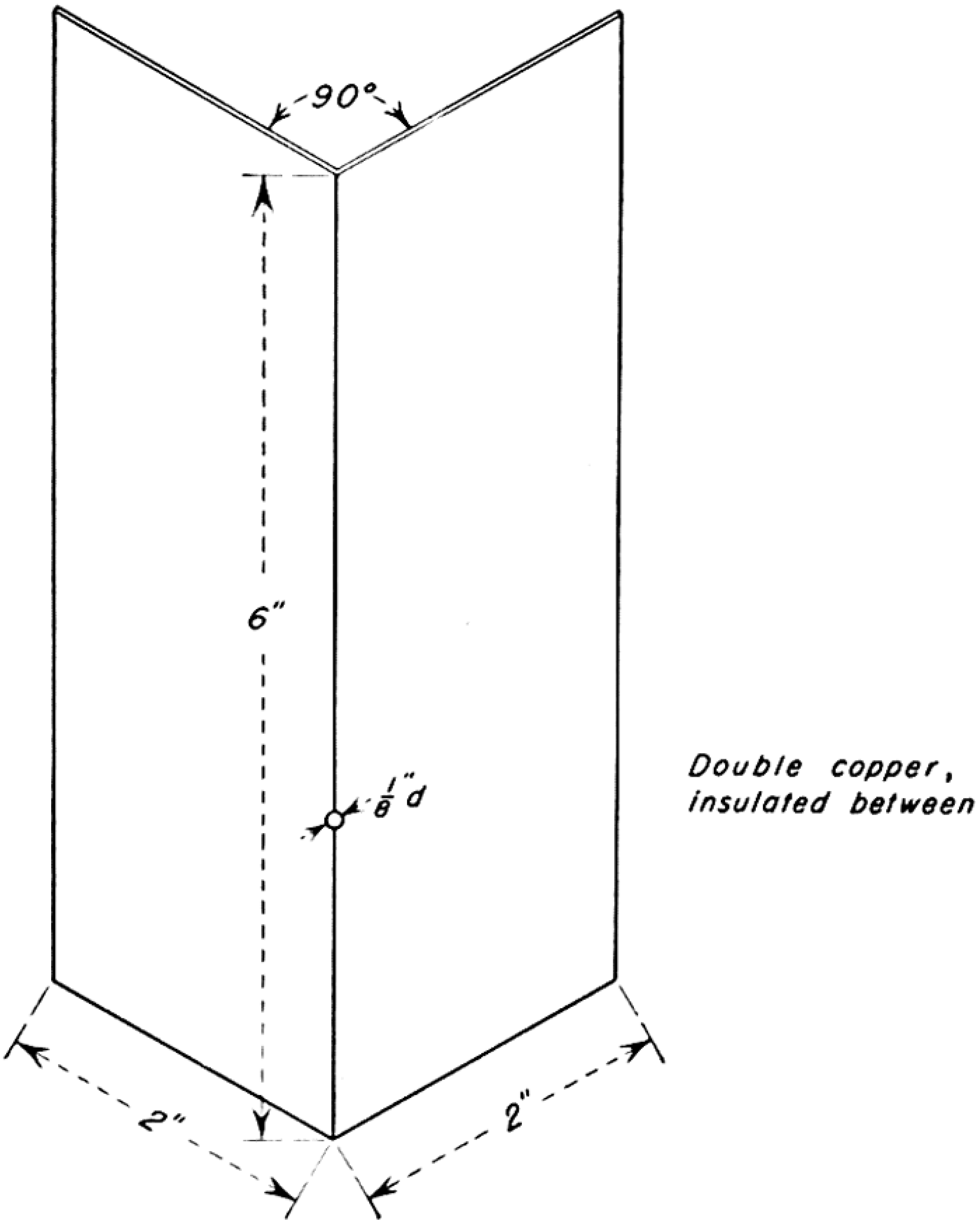

FIG. 4-22. Beam-limiting baffle.

use. Experiments have been carried out using transformer oil, automotive oil (SAE 20), glycerin, water, benzene, Prestone, chlorine and sugar solution, soapsuds, mercury, and various amalgams. From the point of view of simplicity and economy a thin transformer oil appears ideal. This oil is spread upon the surface of the part, and the crystal pressed upon it. However, the oil must wet the part, and it is sometimes necessary to include wetting agents for this purpose.

When the crystal is used to transmit into water or a similar bath, a wetting agent must be used; otherwise small bubbles will form on the crystal and other solid parts and interfere with the transmission of the ultrasonic energy.

When *Y*-cut crystals are used, a stiffer medium is necessary to couple the transverse vibration into the work. Liquids will not normally transmit *S* waves efficiently. A mixture of rosin and oil will, however, couple them satisfactorily, and a one-half mixture of Texaco Marfak and rosin has proved practical. The *Y*-cut crystal may, of course, be cemented permanently to the medium by a wax or cement.

In certain cases it is possible to use a thin foil as a couplant between the crystal and the work. It will be noticed in such a case that the magnitude of energy transmitted depends critically upon the thickness of the coupling. When a liquid is used, the thickness cannot be maintained constant during work, but the same effect can be accomplished by the use of a foil a few thousandths of an inch thick. Any material can be used, the principal consideration being the mass per square centimeter. Aluminum foil is sometimes satisfactory. The use of oils is extremely tricky, and generally the results do not justify the care necessary.

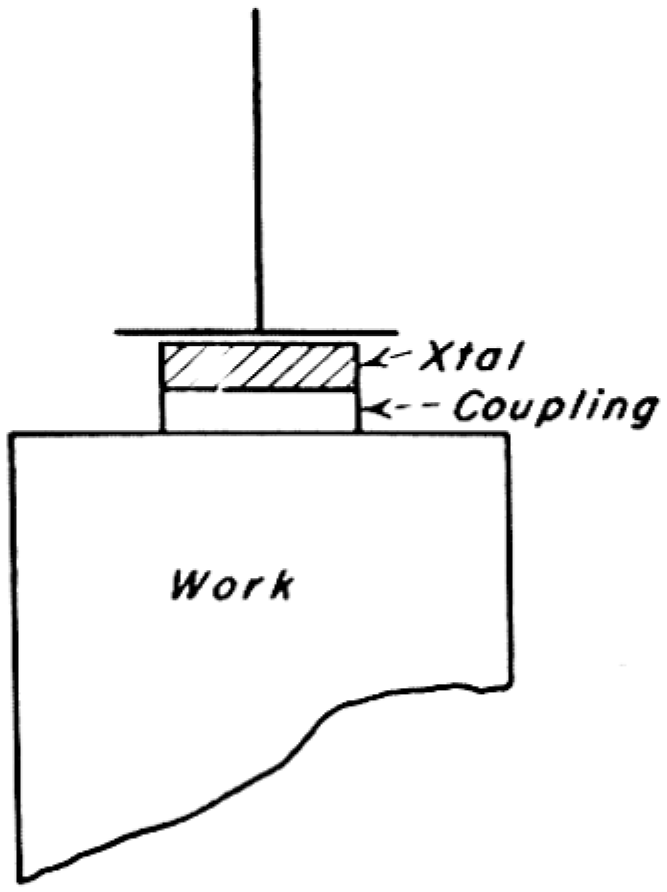

FIG. 4-23. Coupling the crystal to the work.

Face plates may also be used in the same manner as coupling devices, and this is very often done in submarine work. Such a device for example, as Fig. 4-23, shows the addition of a face plate of an acoustic impedance that is between that of the transducer and the medium into which it is desired to operate. This plate acts as the transformer to match the acoustic impedances of the work and the medium.

For this and other reasons submarine transducers are ordinarily made with a medium between the Rochelle salt crystals and the water itself. This medium takes the form of a sound transparent window or plate, which is coupled to the sea on one side and to a liquid couplant, such as castor oil, on the other. The crystal sends waves into the castor oil and through the window into the water.

**Matching the Crystal.** Better results may be expected from a crystal when it is properly matched.[1] This has been borne out both experimentally and theoretically. When the transducer is connected directly across the input of an amplifier, the transformation of energy from electrical to mechanical is poor. However, the addition of an inductance, either in series or in parallel, neutralizes the capacity, and considerable greater efficiency may be expected.

The value of such a coil can be computed from the formula

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where $C$ = capacity of the crystal and holder
$L$ = inductance of the coil

The capacity of the crystal can be measured (by a $Q$ meter) in its actual operating condition, since it will change with the position of the search unit. Once the inductance of the coil is determined for a given set of conditions, it will remain close enough to the correct value to be fixed at it. The coil can be mounted in any manner but should be placed inside the crystal holder for greater convenience.

For a 5-mc crystal ½ in. square, about 38 $\mu$h is a satisfactory value; for 2¼ mc 1 in. square, about 340 $\mu$h; and for 1 mc, about 850 $\mu$h.

Naturally these coils may be slug tuned if it is more convenient, so that they may be varied in inductance after they are mounted in the crystal holder.

One explanation of the theory involved is as follows. In order to get the greatest amount of energy out, it must be delivered into the radiation resistance. A filter is required to do this and in the ideal case delivers to its output all the power put into it. The addition of a coil in series or parallel to the crystal will accomplish this by counteracting the reactance of the unit capacitance at the frequency at which the crystal vibrates.

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[1] W. P. Mason, "Electromechanical Transducers and Wave Filters," Van Nostrand, 1942.

The series coil gives a lower input impedance than the shunt type, and several combinations of coils and crystals can accordingly be put in parallel. This is not true of the shunt type of inductance. This is an important factor in submarine work, where groups of transducers are the rule.

The capacitance of the crystal should not be measured at resonance, since it will give misleading results at that point. A frequency far from crystal resonance is preferable; 1,000 cycles may be used for submarine units.

**Holders for Agitating Liquids.** Crystals are widely used in the fields of chemical, metallurgical, and biological research to drive ultrasonic agitation systems. The systems themselves have been the subject of considerable research and are discussed elsewhere.

The simplest form of holder for agitation is to suspend a crystal in a liquid and force it to vibrate. However, in such a case the damping effect of the liquid itself upon the surface of the crystal is appreciable. Moreover, certain liquids do not act as sufficiently good insulators to the voltages applied to the transducer.

Generally, the radiation from one side of the crystal is used. Therefore, only that face need be coupled to the bath. Holders can therefore be used; and since the crystal gets thinner with increasing frequency, the function of such holders is to support the crystal so that crystal rupture and voltage breakdown will be prevented and the crystal will give maximum ultrasonic output.

Methods and experience with such crystal mounts have been given by Wood and Loomis[1] and others. . The first mounting suggestion was simply to lay the crystal on a flat lead plate. A brass ring was then laid over the face of the crystal to bring the voltage to it. The ultrasonic energy streamed out through the hole in the ring. The diameter of this ring was usually somewhat smaller than the cross-sectional dimension of the crystal in order to prevent voltage breakdown. Lead was used for the crystal backing, since it is a nonconductor of ultrasonics.

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[1] R. W. Wood, "Supersonics," Brown University, 1939.

Gruetzmacher[1] was evidently the first to suggest the use of an air backing. He pointed out that all materials on which the crystal could be laid unavoidably conducted away some ultrasonic energy, and this led to losses in the usable output. He therefore suggested the now well-known expedient of a relieved support of Bakelite or other similar material, which supports the crystal around the edges but leaves a pocket of air behind the main body of the crystal. Ultrasonic output is greater, and damping less.

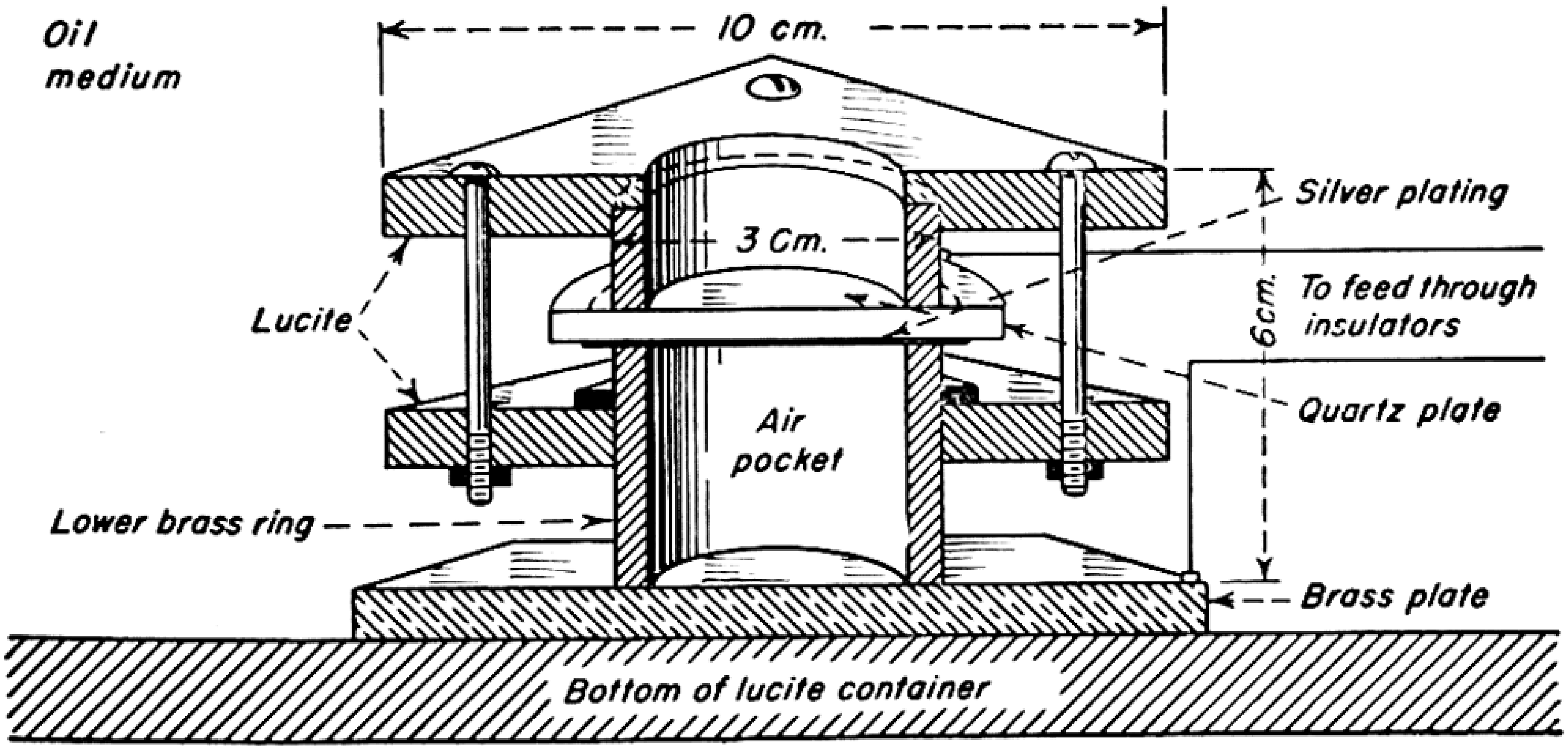

FIG. 4-24. Holder for agitating purpose.

A more recent arrangement for ultrasonic agitation[2] is shown in Fig. 4-24. The crystal is supported by two electrodes with an air pocket behind it. The entire assembly is held together by Lucite plates, which have great resistance to voltage breakdown.

**Submarine Signaling Transducers.** Magnetostrictive systems are commonly used for underwater projection and reception. However, a crystal unit is sometimes used as the receiver even though the projector is a magnetostrictive one.

In underwater listening without a range device, crystal transducers are commonly used. They are superior to the magnetostrictive type in that the band pass is much wider and the sensitivity actually greater. Crystals are therefore somewhat more successful when used to listen for distant noises.

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[1] *Op. cit.*

[2] F. W. Smith and P. K. Stumpf, Ultrasonic Generation, *Electronics*, April, 1946.

There are many ways of mounting such crystals. Mosaics are always used to get greater sensitivity, and Rochelle salts or artificial crystals are preferable because they are more efficient than quartz. These crystals are mounted with their backs fastened to a steel plate. Metal coatings are evaporated on the crystals in the usual manner and are used as contacts for the electrical connections.

In order to keep out the water, a metal plate is usually mounted in front of the unit. The crystals themselves do not bear against this window, which is of steel or a similar material, but the energy is transmitted through a liquid to the window. Castor oil is normally used. There are various special schemes for coupling into the ocean and for the design of such windows.

**The Cable Connection.** The capacity between the crystal and ground must always be kept at a minimum; otherwise a great part of the signal will be lost due to it. Low-capacity coaxial conductors are satisfactory with sufficient shielding, since the receivers are necessarily of high gain. The most important factor is, however, the capacity to ground, since the signals are of high frequency. It is assumed that the crystal is directly connected across the oscillating circuit by means of a cable.

However, various methods of matching the output to the crystal are possible and will be discussed elsewhere. In those cases capacity effects are of less importance.

The cable may be designed to be part of the oscillating circuit capacity. However, in that case only one length and type of cable may be used, *i.e.*, a piece of given capacity. Slight variations will detune the oscillator. It is therefore advisable not to follow this procedure unless it is absolutely unavoidable.

**Lenses and Reflectors for Ultrasonic Work.** Many attempts have been made to focus ultrasonic beams, and some success has been reported. However, results are not particularly striking. Lenses made of glass and of various metals and ground according to the usual optical principles have been tried without notable success. Metals have also been used as the outside skin of lenses, which were then filled with a liquid that formed the actual body of the lens. Copper is generally used. Plastic lenses may be designed, usually of Plexiglas or polystyrene. Other synthetic resins have also been tried.[1]

Curved crystals should be mounted in holders that are matched to their contours. The radius of curvature of button and blank should be approximately the same. It is very important that the curvature of both the crystal and the button be accurately oriented; otherwise the motion of the crystal will be interfered with. In order to keep accurate alignment, indexing pins or keys may be used. When the crystal is small, the button or holder should be made considerably larger in order to give greater surface to follow the curvature.

**Holders for Resonance Testing.** Holders for resonance should be the same as those used in other types of work except that damping must be held to an absolute minimum or it will obscure the points of resonance. Resonance crystals are ordinarily spring mounted; otherwise the pressure of the operator's hand may affect the readings.

Best results are obtained with crystals of ½ in. in diameter when the frequency is more than about 1 mc and of at least 1 in. diameter when it is under 1 mc. Naturally, the entire face of the crystal must be seated on the work; and when the work is small, the crystal must also be small.

When crystals are designed for resonance work using longitudinal waves, as they have always been to date, it is particularly important that the crystal does not also produce shear waves, which travel in the work at a different velocity and obscure the results by spurious peaks. This can be avoided by making certain that the crystal button fits about the edges of the crystal extremely tightly and constrains it from vibrating in the $Y$ dimension.

**Interferometry.** Special ultrasonic crystal mountings are necessary when they are used in an interferometer system. In such work the experimenter assumes great purity of wave shape. He must also closely estimate the amount of radiation, etc. An ultrasonic interferometer works on the reflection of waves from a plane reflector back to their source. Resonances are then noted as either the reflector or source is moved (usually the reflector). This can be done by noting the dips in the current flowing in the electrical parts of the system, usually the plate current of the oscillator that drives the crystal.

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[1] P. J. Ernst, *J. Sci. Instruments*, **22**, 238 (1945).

In order to make these dips as sharp as possible, the damping must be a minimum. The crystal is therefore carefully plated and mounted for optimum vibration and minimum damping. The general idea is apparently to get a perfectly pistonlike vibration of the quartz.[1]

**Holders for Microscope Use.** In biological or similar work the worker sometimes wants to observe the action of ultrasonics on microscopic bodies or particles. In order to do this, a special holder must be made, which will agitate the substance under observation while it is in the microscope.

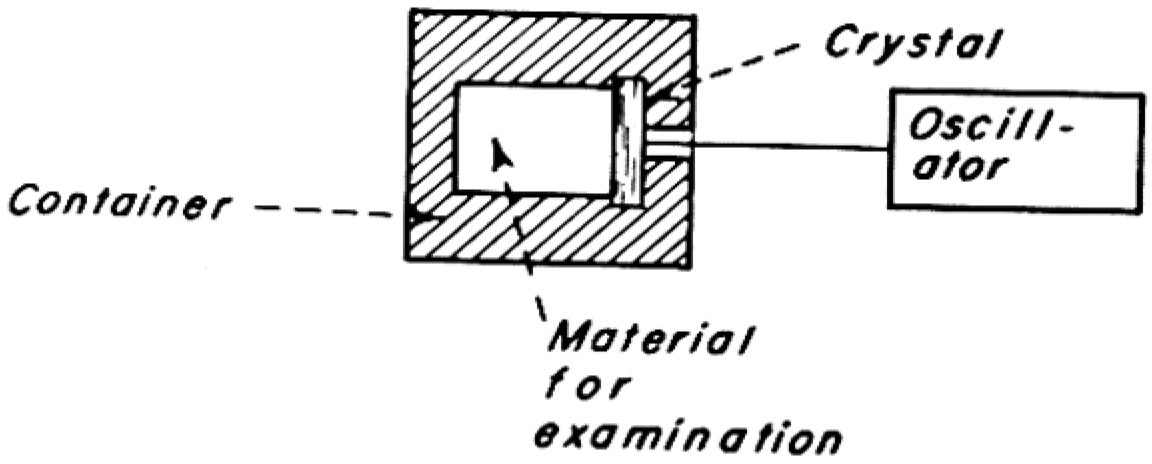

FIG. 4-25. Holder for microscope use.

Such a holder may be in the form shown in Fig. 4-25. The crystal drives a bath in which the object is suspended. The microscope is so arranged that the observer can look directly down into the holder, which is of suitable physical dimensions to fit on its stage.

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[1] F. E. Fox and G. D. Rock, An Ultrasonic Source of Improved Design, *Rev. Sci. Instruments*, September, 1938.

## CHAPTER V

# RESONANCE AND REFLECTION

The phenomena of resonance are the basis of a whole class of ultrasonic instruments, most of which measure the thickness of a medium that exhibits its effects. Such instruments can be used as altimeters, submarine depth finders, and thickness-measuring devices.

At the same time the occurrence of resonances seriously impeded the development of ultrasonic instruments that did not work according to resonance principles but nonetheless had accidental resonance integral to their nature. It did this by causing extraneous readings, which made it impossible to interpret results correctly. These instruments were chiefly the ones which relied upon the continuous transmission of ultrasonic energy through a medium. The formation of resonances is therefore a matter of primary importance in ultrasonics and should be extensively considered.

Certain test functions, such as the investigation of bond adhesion and flaws in thin films, can also be carried out by resonance instruments. Only one side of the material need be accessible. Resonance systems work on fundamental resonances up to about ½ in. of steel, *i.e.*, ½ mc. Some results can be obtained up to 4 in. by harmonic methods, but interpretation is much more difficult. The usual considerations for curvature of the part, surface, etc., remain valid.

**Resonance.** The term *resonance* refers to a physical property possessed by a medium because of its dimensions. Such a characteristic may, for example, cause the body to begin to vibrate at a given natural frequency when it is brought into the neighborhood of another body that is already vibrating at that frequency. This action may be observed in a tuning fork or piano.

The induced vibration will continue, sometimes for considerable lengths of time, and will decay only when the natural friction of the medium causes it to do so. In some cases there may be several frequencies or modes in which such a body might vibrate, usually related to one another harmonically or in some other manner. Thus an article might, for example, oscillate at 60 cycles and also at 120 cycles, as well as at other frequencies.

Most bodies also exhibit another characteristic similar to the first. In this case the body will be forced to vibrate at a frequency determined by a neighboring vibrator. However, it is not a natural frequency due to its dimensions at which the body is oscillating. Therefore, when the medium that is inducing the vibration is removed, the driven unit will quickly stop its action. Moreover, the size of the oscillations will be considerably less than in the case of natural ones. More driving power is therefore required. This operation is similar in theory to driving a crystal transducer at a frequency other than its resonant one.

Both of these types of resonance are referred to as *forced* ones, since they are cases in which the vibrating body is actually driven. It may be shown, as indicated, that the first case, in which the driving frequency coincides with the natural one, is the one where a maximum motion or vibration occurs. Cases have been recorded in which such vibrations reached proportions where large structures were destroyed. It can therefore be seen that the force is a powerful one.

When resonance is referred to in ultrasonic systems, it is usually somewhat different from these cases, although the general nature is closely similar. The only type of resonance that is of much interest, because of the small amounts of power needed in most ultrasonic systems, is the case where the driving and driven resonances coincide. It has already been mentioned that in that case the motion is a maximum.

In most ultrasonic systems resonance occurs when the electrical frequency is varied until the ultrasonic wavelength is related to the distance traveled by an integer multiplier. In other words, there is a certain whole number of half wavelengths in an entire path of travel. In such a case the driving electrical oscillator will be called upon for a minimum amount of power output, and the greatest proportionate amount of ultrasonic energy will be produced in the material.

Thus, certain valuable characteristics of resonance become immediately apparent. First, since ultrasonic resonance is defined as that condition (of dimensions) which requires a minimum of power to maintain, a part can continue to oscillate without requiring additional input power, except enough to overcome the material's internal damping. Therefore, in pulsed systems a sharp shock of excitation may be impressed on a material, and characteristics of that material deduced by the length of time that the system continues to ring. Again, a series of different frequencies may be applied to a medium, and its characteristics deduced by noting which frequencies require minimum driving power, *i.e.*, resonate. Also since a part can be of such special dimensions that it will resonate at a particular frequency, it is obvious that the dimensions of a part can be deduced by noting which frequencies will resonate it. Resonance occurs only when reflected ultrasonic waves build up in the same phase with those transmitted. When this occurs, the thickness is an exact multiple of half wavelengths. It is therefore easy to make a table of material thickness versus wavelength or frequency for any one material. Different tables are obviously required for different materials, since velocities differ in different media. Such a table is shown in Fig. 5-1 for steel or aluminum, in both of which waves travel at about the same velocity. By the use of this information, the thickness of any medium that transmits ultrasonic waves can readily be determined.

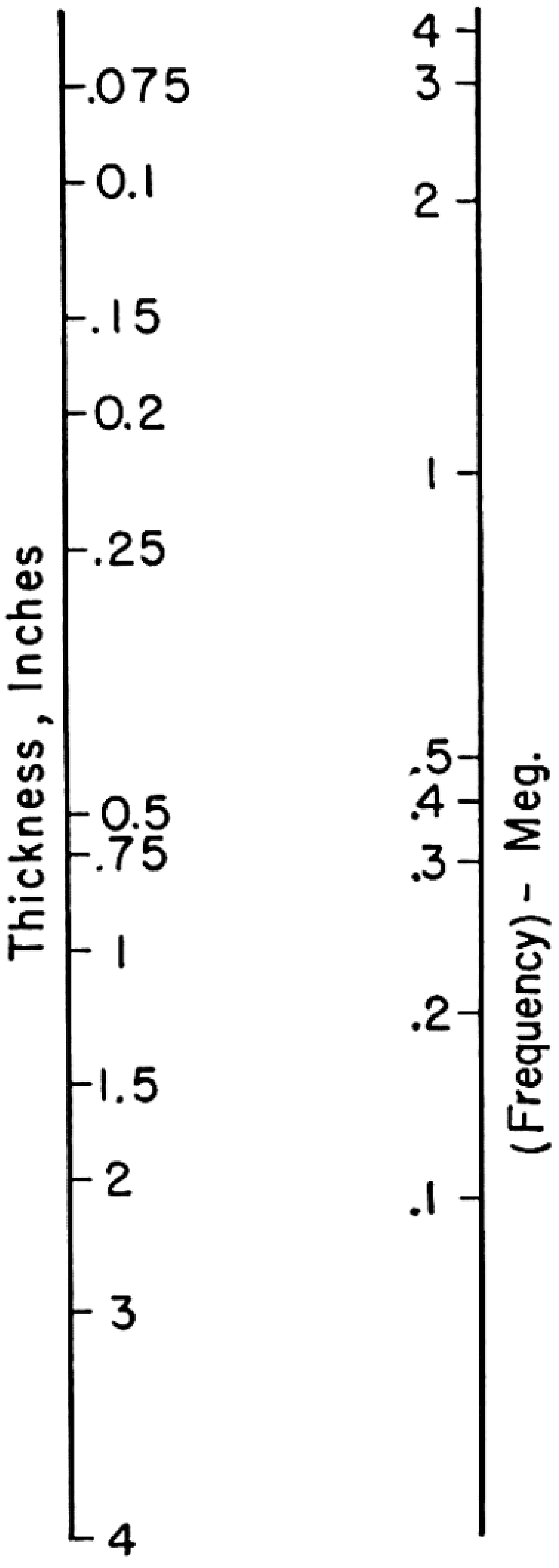

FIG. 5-1. Relation of thickness in steel to frequency.

In ultrasonic systems the transducers are sharply tuned, and the material itself often responds to frequency variations very sharply. As damping is added to any part of the system, it tends to tune less sharply, *i.e.*, to become more broad band. For resonance tests, it is naturally preferable that the tuning be as sharp as possible. This sharpness is the usual rule, and as a result an ultrasonic system will vibrate at only one set of frequencies.

Resonance effects in ultrasonic systems may cause interferences that are difficult to control. These effects are due to what are referred to as *standing waves* and are related to the way in which the reflected and incident waves combine to form a resultant pattern. It is not necessary for a part to have resonant dimensions for standing waves to appear. Any system in which waves are propagated will exhibit some tendency to produce them.

**Standing Waves.** If a wave is sent out into any type of finite system, sooner or later it will reach the end of the medium in which it travels, be reflected, and return toward its source. However, during the time of travel other waves have been continually sent out, and each, in turn, is reflected. After a given time the whole system may reach a state of equilibrium, in which all the waves both transmitted and reflected are summed up (Fig. 5-2). However, this summation will not necessarily be uniform over the entire transmission distance. For example, considering only two waves, if the time of travel is correctly chosen, they may be found to be 180 deg out of phase at certain points, entirely in phase at other points, and at varying phases at still other points. If the resultant disturbance is then measured over the entire path, that disturbance may vary in ampli-

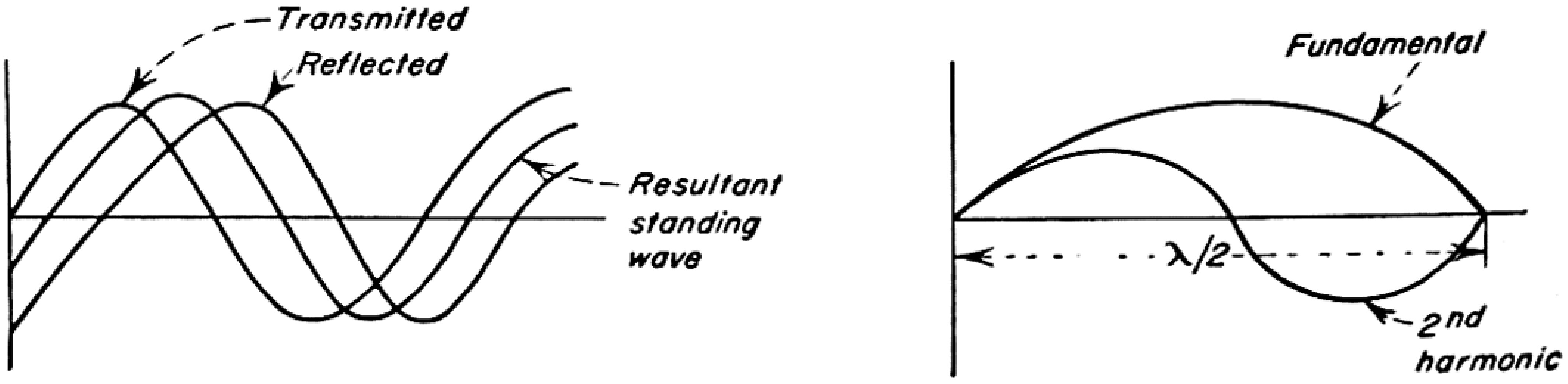

FIG. 5-2. Action of standing waves.

tude at different points because of addition and cancellation effects. These variations may and usually do become fairly regular over the transmission path; and since they do not seem to vary with time once the system reaches its equilibrium, they are referred to as *standing waves.*

The relation between resonance and standing waves is readily apparent. Actually the formation of standing waves may be considered as a sort of resonance.

The case above can be applied to ultrasonic waves. When an ultrasonic wave is transmitted into a medium and the path it travels is greater than a half wavelength (which it practically always is), the wave will be reflected from an interface or from any change in elasticity or density. This reflected wave will combine with the transmitted one, and a set of standing waves will result.

The first mention of standing waves in continuous-wave systems occurred in Shraiber.[1] He pointed out the possibility of interference between those ultrasonic waves reflected by a part and those being transmitted toward it. The particular case of interest to him was that in which nodes formed on the surfaces of the media where the waves were being reflected. Since he was trying to transmit ultrasonic energy through these materials, this was particularly troublesome. If the piece had a varying thickness, no energy seemed to be transmitted through it (at those thicknesses where standing waves formed) and the receiver acted as though the energy were interrupted by a discontinuity in the material. The person operating the instrument in such a case could not interpret his results. Such conditions were considered theoretically in Chap. II.

It is, however, more common for the standing waves to indicate as differences of energy level as the part is moved between two transducers. This occurs because of minute differences in distance among various parts of the system, which are nonetheless appreciable fractions of ultrasonic waves. The entire standing-wave pattern may thus continuously shift as a test is carried out, and all sorts of extraneous responses occur.

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[1] D. S. Shraiber, Testing of Metals by the Use of Ultrasonics, *Z. Lab.*, **9**, 1001, 1940.

One of the main problems in the use of continuous ultrasonic waves lies therefore in the fact that these resonances or standing waves may occur in the medium itself, in the coupling medium, in a submerged part, or in any part of the entire ultrasonic signaling system where there is a reflection from a change in the acoustic impedance. The indicator may then be influenced more by the difference caused by the standing waves than by the ultrasonic signal itself, and the system becomes useless, since it is impossible to interpret the results.

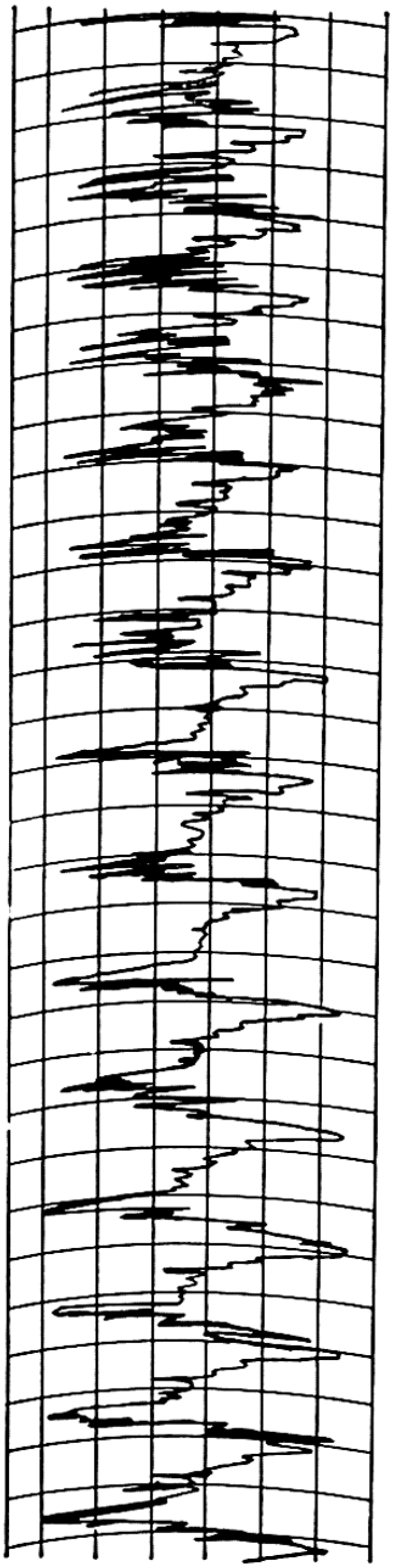

FIG. 5-3. Standing-wave indications.

Figure 5-3 is an oscillogram of an actual ultrasonic test in a liquid bath. The variations are caused by standing waves and not by flaws in the material. These standing waves shift with movement of the piece under test.

The presence of standing waves or reflections in a medium that attenuates the ultrasonic signal causes additional losses of energy. Ultrasonic waves will be attenuated by any medium that has viscosity. This, of course, is a characteristic of all materials to some degree. Since the amount of ultrasonic attenuation is a function of the size of the signal and since the reflections of energy cause a rise in the internal signal intensity, it may be qualitatively stated that the greater the amount of reflection in a part the greater will be the attenuation of energy within it. Thus, for a fixed amount of incident ultrasonic power, if the reflections become larger, the losses also become greater.

Since any difference in acoustic impedance will cause a reflection, and since any boundary between materials or within a material constitutes such a difference, there will always be reflections at boundaries.

This reflected energy will combine to form standing waves.

In order to do away with standing waves, reflections must also be eliminated. To accomplish this, it is essential that the media in the path of the ultrasonic beam be matched acoustically. In other words, the transducer must be matched to the media, the media to the receiver, etc.

However, matching two media ultrasonically poses certain problems. For example, resonances may be designed against for a certain set frequency; but when the frequency is varied, the same result will no longer be accomplished.

The greater the amount of reflection in a body the more it will discriminate with respect to frequency. A piece in which an ultrasonic standing wave exists acts something like a resonant electrical circuit. It will pass only a small range of frequencies. The greater the amount of reflection the more sharply tuned it is. In other words, the more gradual the change in acoustic impedence is between parts of an ultrasonic system the less selective to frequency those parts are and the fewer reflections there are.

Another approach to the problem is commonly used in ultrasonic light cells, where the ultrasonic energy is to be continuously modulated. In such cases, an absorbing material is so placed that it absorbs the ultrasonic energy after the modulation effect has taken place. There is no reflection and accordingly no build-up of energy and no resonance or standing waves.

This effect may be observed in testing materials for thickness by resonance, where placing a finger or other absorbing medium on the back of the part causes all the resonance peaks to disappear because of the loss of reflection.

The phenomenon has been applied in tanks, etc., to kill reflection. Various absorbing media such as animal wool, gelatin, and similar substances have been used. Scattering media may also be applied in this manner. In that case the wave is broken up into many small parts and therefore cannot reinforce itself. A material with many small irregular protrusions will accomplish this.

**Resonance Thickness Measurement.** To repeat, the relation between frequency and wavelength may be stated as follows, since ultrasonic waves travel at different velocities in different media. The formula is

$$\lambda = \frac{c}{f}$$

All ultrasonic systems for measuring thickness by resonance are based on this relationship. The wavelength is varied until a point of maximum reflection is located. This is the resonant point. If the part under test is allowed to vibrate only in its fundamental mode, there will be only one such point.

In the case where the thickness of the medium is entirely unknown, the fundamental and a number of harmonics may all indicate. Under these circumstances two adjacent readings are taken. These will be $1/n$ and $1/n - 1$ of the total thickness $t$. By setting up two equations and solving them, a final equation for the thickness can be derived:

$$t = \frac{r_1 r_2}{r_1 - r_2}$$

Occasionally, when the resonant principle is applied to the testing of very thick sections, so many harmonics appear that it is difficult to interpret the pattern. In such situations every $n$th peak can be counted, and the results substituted in a revised form of the relation.

$$t = \frac{N r_1 r_2}{r_1 - r_2}$$

The fact that only one pip occurs on a particular instrument obviously does not indicate per se a fundamental mode. The factor that determines the number appearing is, of course, the range of excitation and indication.

Therefore, when testing a material or reading its thickness by the resonance method, the most general information is not any one resonant point, but it is rather the distance in frequency between successive resonances. Pieces that are multiples of one another in their thickness dimension resonate at many of the same frequencies, but their total spectra will not be the same. Thus if a particular piece indicates resonance at 1, 2, 3 mc, etc., it means that the actual fundamental frequency is the difference between two different frequencies at which higher modes of resonance occur. Thus, in this case the resonant frequency is 1 mc. It may be seen from the above example that at least two harmonic resonant points are necessary in order to determine the fundamental resonance.

In a like manner any material, solid, liquid, or gas, can be investigated and its thickness determined by getting two successive resonant points and subtracting them. It is always advisable to test the piece over as wide a range as possible, since the accuracy to which the readings can be made would be greater by testing over a range that makes small variations more readily noticeable. The wider the range the greater the number of harmonics that will indicate.

This does not mean that it is impossible to test in a fundamental mode, *i.e.*, one where there is one nodal plane in the material. As a matter of fact, on a practical level it is possible to test on a fundamental up to about ½ in. in steel under good working conditions. However, when parts are thicker than this, the fundamental mode is no longer used and harmonics must be used.

The accuracy of the resonance method of test is essentially limited only by the willingness of the person using it to resort to very exact electrical and mechanical devices. For example, precise gear-driven knobs for controlling the frequency may be carefully calibrated and used with those types of screw drive common on interferometers. Moreover, the associated electrical circuits can be made tremendously selective, so that the resonant points are very narrow and frequency readings extremely exact.

Interferometers have been constructed with accuracies in the order of 0.2 per cent. However, the average ultrasonic resonance instrument for the testing of material probably approximates 2 per cent more closely.

This type of ultrasonic instrument has very wide applications in the measurement of the thickness of materials and in the testing of thin bonded articles such as silver-plated aeronautical bearings or bimetallic strip. It can also be used for measuring any thickness or for locating any flaw in a medium that is not more than about 4 in. thick. However, the instrument is most suitable when used on a large number of articles that are very similar to one another in thickness and in which small variations must be located. If the range of thicknesses that must be tested is very wide, separate ranges of test and separate crystals must be used. Generally speaking, the narrower the range over which a crystal is used and over which the oscillator operates the sharper the resonant points will be. As the instrument is tuned away from crystal resonance, there will be a considerable loss in indication amplitude.

An instrument might therefore be reasonably set up to test from about 0.035 to about 0.075 in. in thickness. If it were also desirable to test an article 0.25 in. thick, a different range and a different crystal would have to be used. Generally a 1 : 2 thickness range is satisfactory in those instruments which have a swept frequency.

**Testing Materials by Resonance.** The principles of resonance have been successfully applied to the testing of materials, and several commercial instruments are now available.

**Exciting Resonance.** Almost any ultrasonic generator is capable of exciting resonance in thin sections. Radio-frequency oscillators of almost any sort are suitable for this method of operation. A generator that can be used for other methods of test will provide enough power for resonance methods.

**Acoustic Impedance.** The acoustic impedance represents a characteristic of the medium that is closely akin to electrical impedance. It is determined by all the elastic properties of the material. Such an impedance may be thought of as "characteristic" in a technical sense when it is the impedance that would be offered by an infinite extent of the media, *i.e.*, when there are no variations in that impedance within the material (and therefore no reflections). In a like manner the electrical analogy may be carried further, and it may be considered that when a piece of any given impedance is matched into another medium of the same impedance, or when a medium is terminated in its own characteristic impedance, then the combination will act like a single part of identical material and there will be no reflections at the interface. Such a condition is difficult to attain in ultrasonics.

**Matching Impedances.** Impedances can be matched by keeping them alike; however, it is obvious that situations often occur in ultrasonics where energy must be transmitted from one medium into another of vastly different impedance. When that occurs, some method of matching impedance becomes necessary.

One possible suggestion is the addition between the two media of another part that has an impedance of approximately the geometric mean of the other two impedances. Even better results may be accomplished by interposing a number of such parts, each having an impedance that is the mean of that of its two neighbors (see Fig. 5-4).

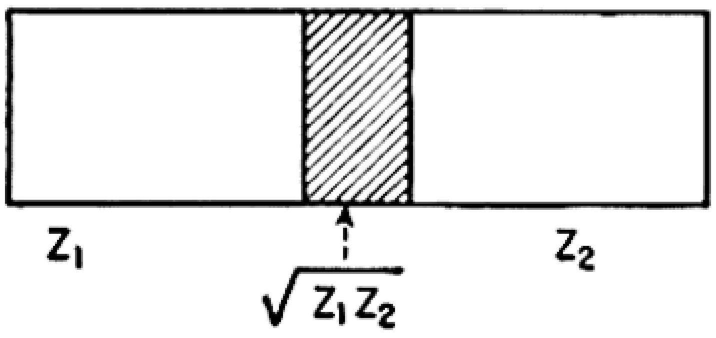

FIG. 5-4. Method of matching impedance.

Such a combination acts as a sort of impedance transformer. Naturally, the greater the number of sections the less the reflection at any one interface and the more efficient the matching.

Moreover, if the intermediate material is of the proper wavelength dimensions, reflections from the two sides will have a tendency to cancel out. This may be approximated with sections of a quarter wavelength. Very few net reflections will result in such a system.

When a crystal is used, one material to be matched is quartz, and the matching media can be fastened directly to the crystal face if desired. It will then also act as a protecting face plate.

Experimentally speaking, the use of such materials for matching has not been very successful, although rough approximations of the desired results may be demonstrated.

**Standing-wave Ratio.** As already indicated, whenever an ultrasonic wave travels in a material with boundaries and the part is more than a half wavelength in length, some standing waves will result. Since this condition always occurs, it is convenient to have a method of indicating it. However, a similar situation occurs in electrical systems, and the analogy is obvious. The same nomenclature will therefore be used here.

The standing-wave ratio in ultrasonics will therefore be defined as the relation between the energy of the ultrasonic wave at its loop and that at its node. This in turn depends on the relation between terminating and characteristic impedance. The ratio is defined by the formula

$$\mathrm{SWR} = \frac{Z_t}{Z_0}$$

where SWR = standing-wave ratio
$Z_t$ = terminating impedance
$Z_0$ = characteristic impedance

A medium that is terminated by an ultrasonic impedance equal to its characteristic one acts exactly like a single part of homogeneous material. There are therefore no standing waves; both impedances are equal, and the standing-wave ratio is 1.

**History.** *Submarine Apparatus.* German interest in submarine warfare led to what may have been the first practical application of resonance to the measurement of thickness, although in this case the thickness was the depth of water in which a submarine or ship was traveling. A patent was issued for this purpose in 1921 and is illustrated in Fig. 5-5.[1]

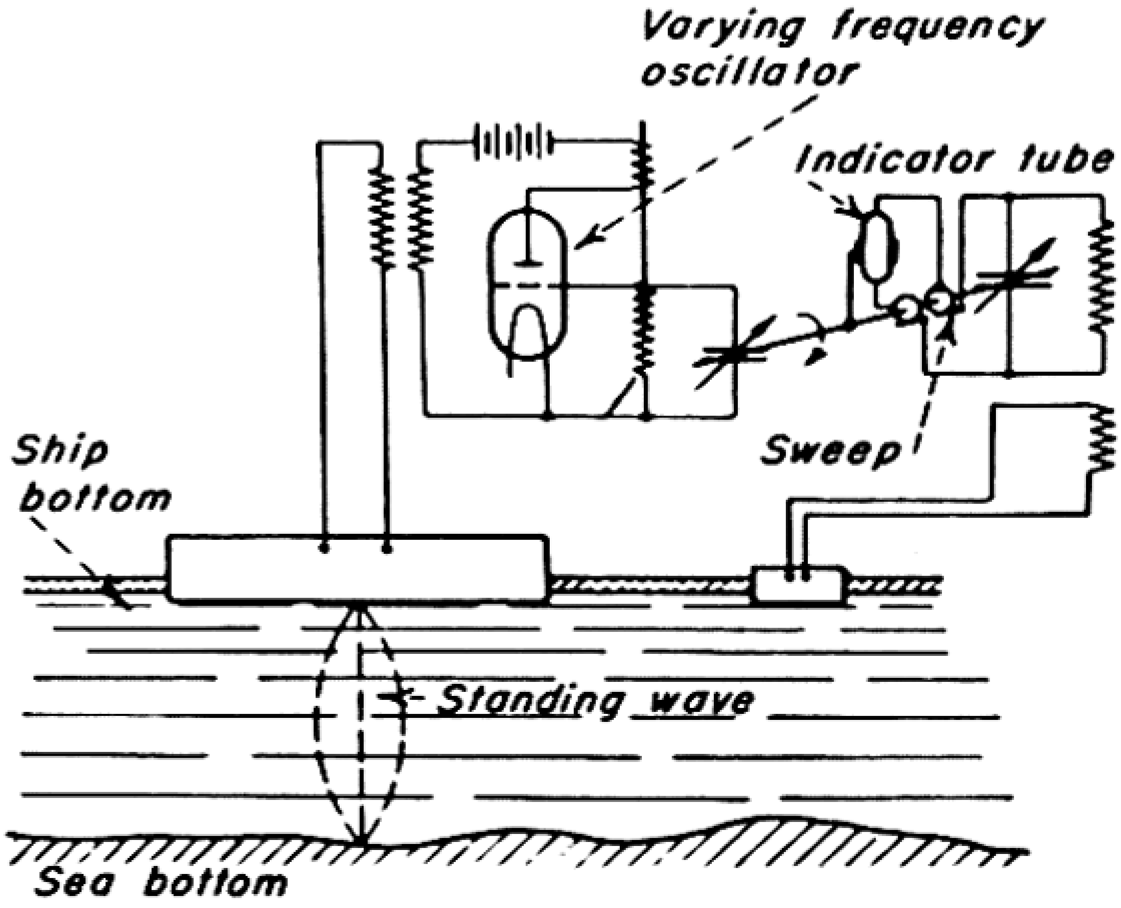

FIG. 5-5. German depth-sounding device.

The operation of this apparatus is of interest, since it represents the action of all systems of this class and depends upon the fact that a signal of the greatest intensity will be indicated by an instrument when the standing-wave system is so set up that the wavelength is a specific submultiple of the thickness of the material. The submarine apparatus consists of an oscillator that transmits ultrasonic vibrations and of a receiver with indicating meter. The transducers are crystal plates.

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[1] A. Behun, German Patent 464,516.

The frequency of the transmitting oscillator is varied over a range that includes in it those frequencies necessary for measuring the average depth of the water. This range covers a frequency that is specifically resonant at the depth under test. At the same time that the transmitter is swept, the receiver frequency is also tuned in a like manner over the same frequency range. In this particular piece of apparatus both oscillator and receiver are controlled by condensers that are rotated on the same shaft. If at any point the transmitter is sending out some one frequency, the receiver is therefore also tuned to that same frequency. The receiver will indicate a maximum voltage at the point where the depth of the water is resonant to a frequency being transmitted by the oscillator. The indicator is a neon bulb, which is in the output of a receiving amplifier and which glows with a varying degree of brightness as the received voltage changes. This is somewhat difficult for the operator to interpret. Therefore, in this particular patent the light also rotates on the condenser shaft behind a calibrated dial. When the bulb flashes, the calibrated dial can be directly read in frequency, wavelength, or depth of water. Obviously any other form of indicating system may be used.

The disclosure also indicates that a second crystal for reception can be placed either directly next to the sender or anywhere else in relation to the transmitting crystal.

**Interferometry.** The interferometer is an instrument for exactly measuring the wavelength of any wave motion. These instruments are made for ultrasonic use and operate on the same principle as those made for use with other kinds of radiation. Generally speaking, an interferometer can be used only in liquids or gases, since it works on the principle of movement within the media. The instruments measure the distance between successive nodes. The measurement is accomplished by very exact calibration of the movement of a mechanical part of the system. The principle of the interferometer in ultrasonics was first stated by Pierce in 1925.[1] The general operation is as follows:

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[1] *Proc. Am. Acad. Arts Sci.*, **60,** 271 (1925).

A crystal source transmits ultrasonic waves into the medium; they impinge upon a parallel reflector and are reflected back to the source. This parallel reflector is ordinarily mounted on a very fine screw, which can move it small fractions of a centimeter at a time. As the reflector is moved through a given distance, the plate current of the oscillator that provides the driving force for the sending crystal is observed and points during which the current is a minimum are noted. Naturally, the principle can be applied to instruments that are built in various forms, and there has been considerable literature on interferometry. A more refined instrument, for example, was designed by Hubbard and Loomis.[1]

However, all these instruments are essentially of the same class and are capable of very fine adjustment and measurement. For example, instruments can be made that will give an accuracy of approximately 1 part in 2,500 when used for wavelength measurement. Because of the relation between wavelength and frequency, this same instrument can be used for the measurement of velocities in liquids or gases, and a good many velocity measurements have been made in all types of liquids using it.

As already indicated, there has been considerable experimentation in the field, most of which is not of any great interest to anybody except the specialist in interferometry. However, a few of the more significant experiments may be mentioned. Klein and Hershberger[2] built a modification of the instrument, which used Rochelle salt as the driving element, and also tried magnetostrictive materials for transducers. They also worked out methods for measuring the characteristics of minute quantities of liquids. Various other experimenters have measured reactions under special conditions such as low temperature, etc. Values obtained by the interferometer are usually more accurate than those required for practical work.

Another method of interest in measuring wavelength was suggested by Brillouin. His system is based upon the fact that when the standing waves are set up ultrasonically in a translucent material, the pattern formed in the material by successive rarefactions and condensations affect the light and the resultant pattern can be investigated by optical diffraction methods. Such methods are described at greater length elsewhere.

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[1] *Phil. Mag.*, **5**, 1177 (1928).

[2] *Phys. Rev.*, (2) **37**, 760 (1931).

The interferometer depends for its accuracy upon the care with which it is mechanically designed and constructed. Figure 5-6 shows a pictorial diagram of a simple interferometry system.

From the above relation, it may be seen that the thickness of an article is inversely proportional to the frequency at which it will resonate and can be expressed for any material as

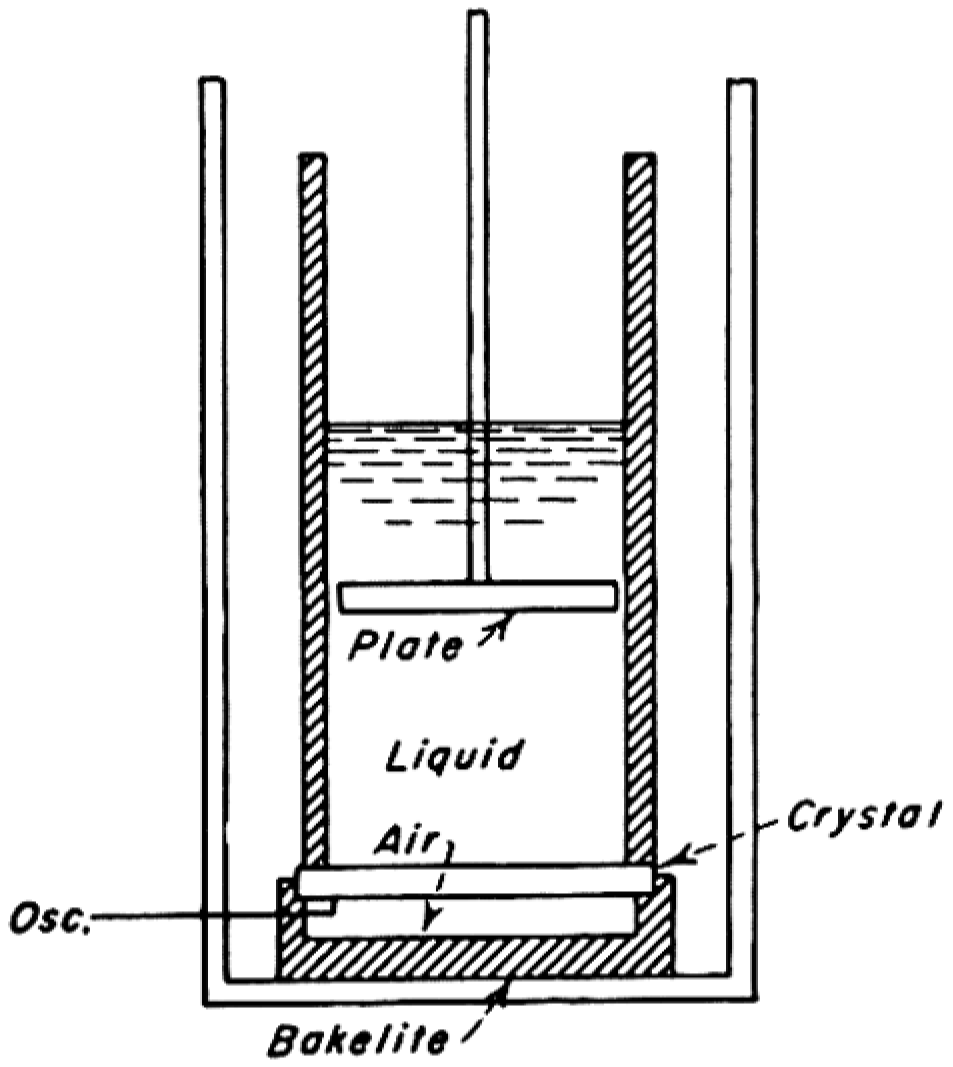

FIG. 5-6. Simple interferometer.

$$t = \frac{k}{f}$$

where $f$ = frequency in kilocycles
$t$ = thickness in thousandths of an inch
$k$ = a constant, which for steel or aluminum is 121,000

Constants for other materials can be calculated from

$$k = \tfrac{1}{2} c$$

where $c$ is the ultrasonic velocity of the type of wave being used. However, any part that scatters the waves heavily, either by having a large number of inclusions or because of badly pitted or corroded surfaces, will not reflect enough energy for resonance use. Such media are very difficult to test. Moreover, a material must not absorb energy strongly either within itself or at its boundaries or, generally, rest on absorbing surfaces. Under test conditions, for best results the part under examination is accordingly supported away from the table on which it rests.

**Indicating Resonance.** Resonance may be indicated by two basic methods, *i.e.*, by either the effect upon the ultrasonic signal or that upon the electrical system which generates it. Thus in the former case the transmitted ultrasonic wave may be received after reflection, indicated on a cathode-ray tube, and viewed.

The maximum amplitude of signal will indicate a resonant condition.

In the second type of instrument the fact that the ultrasonic system is resonant causes it to draw less power from the plate circuit of the driving oscillator. A plate current meter will therefore show a drop when resonance occurs. Other conventional methods of indicating the change in plate dissipation are also satisfactory.

**The Complete Resonance System.** Resonance systems are of two types because of the phenomena described above. These two systems are indicated in Fig. 5-7. The first system is simpler but sometimes not so convenient. In it the effect of resonance upon a transmitting system is used to indicate results. This effect may be indicated directly or amplified. The sender is swept over the entire frequency range necessary for the test, and resonances indicated. It is then necessary to take several different resonances and calculate the fundamental. This is ordinarily done by having a chart calibrated against thickness or by having some kind of automatic device for indicating the thickness directly.

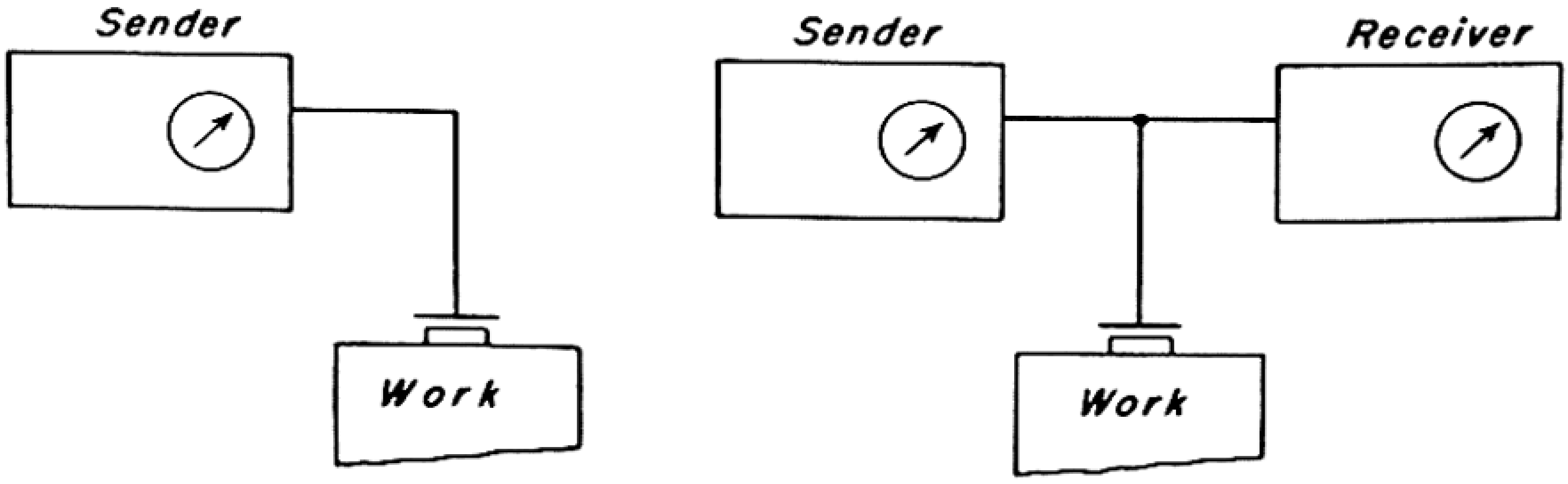

FIG. 5-7. Resonance systems.

The system may also consist of separate senders and receivers, using either one or two transducers. In that case the amplifier must be capable of receiving the transmitted signal, either by being tuned to it or by being of sufficiently broad band to pick up the entire spectrum of the oscillator. The oscillator is swept over a frequency range in the usual manner. The output of the receiver is indicated in some fashion and calibrated in the same manner as the first type of unit.

The above principles apply equally well to continuously oscillating or pulsed systems. The most successful method of avoiding standing-wave problems in test systems that do not operate by resonance consists of pulsing the ultrasonic energy. When this is done, the ultrasonic vibrations will decay between successive pulses and standing-waves cannot build up to the same degree as in continuous systems.

Nevertheless, pulsed ultrasonic systems may be successfully used for resonance work. Almost all these systems use separate oscillators and receivers, since the change in output at resonance is so minute that it is difficult to measure. When a pulsed system is used for resonance, that condition indicates as a swelling out of the pulse, as shown in Fig. 5-8 where *a* is a nonresonant condition and *b* is a resonant one.

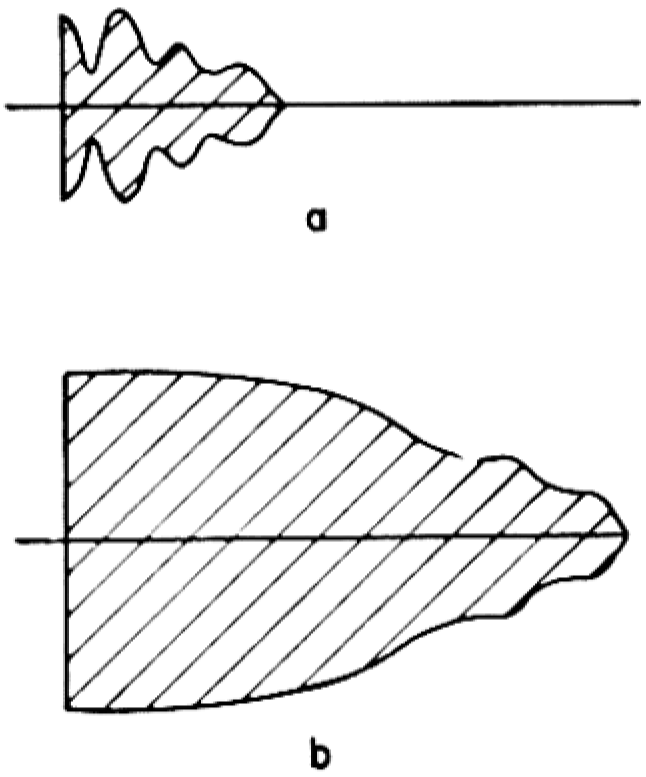

FIG. 5-8. Pulsed resonance indications: (*a*) not resonant, (*b*) resonant.

Resonant test equipment may use either crystals or magnetostriction devices, but crystal use is far more common. The entire discussion is applicable to either type of transducer.

**The Oscillator.** Any of the common types of oscillators, such as that indicated in Fig. 5-9, may be used. For wobbulated systems, a mechanically tuned condenser may be used. When motor-driven condensers are used, great care must be taken to eliminate the hash caused by bearings, contacts, etc. However, these systems are now the ones most commonly used.

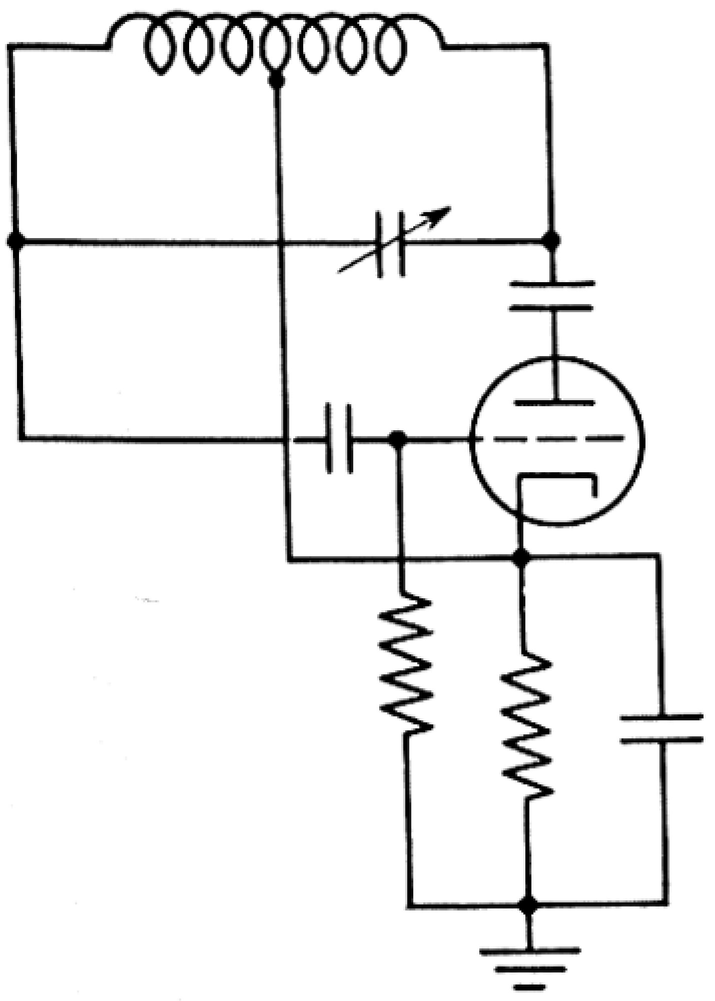

FIG. 5-9. Simple oscillator.

The oscillator should be designed to give as constant an amplitude of output as possible. If the amplitude of the radio frequency produced is not constant, the trace of an oscillographic indicator will be displaced and the pips appear on the displaced sweep. An oscilloscope is probably the most satisfactory indicator, although a plate current meter is occasionally used. However, the output of the oscillator must be amplified before it is fed into the plates. A typical system is shown in Fig. 5-10. Filters are sometimes included to eliminate the radio frequency, but the ordinary amplifier will do this in any case. The gain needed is not great and is usually between twenty and several hundred. No compensation of any type is required for frequency.

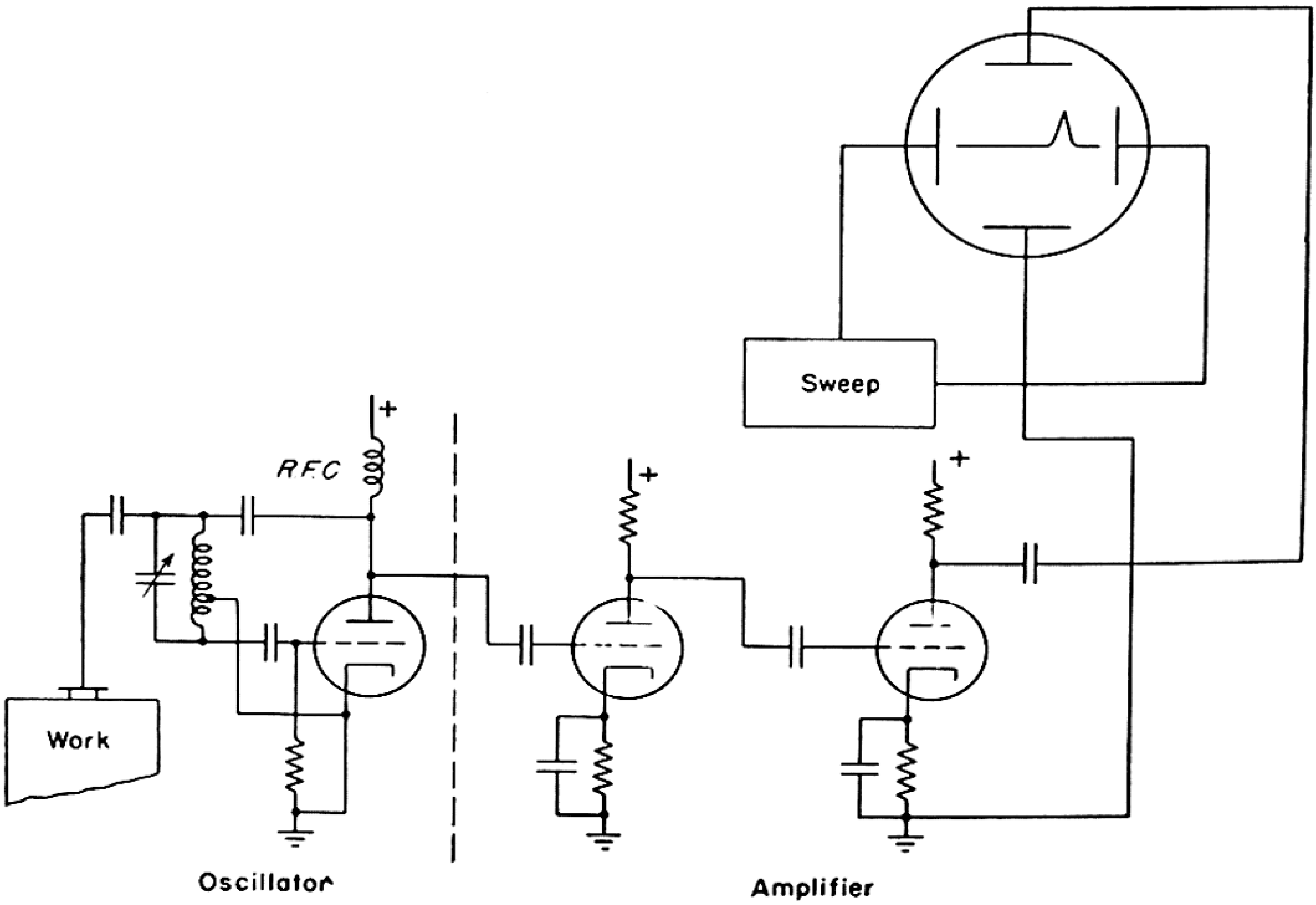

FIG. 5-10. Typical indication system.

Each coil used in the oscillator should cover one testing range. These ranges are usually about a 1:2 ratio; *i.e.*, from 0.010 to 0.020 in. thickness in steel, 0.020 to 0.040 in., etc. Since most thickness testing is carried out on parts whose dimensions are at least approximately known, each range should have the dimensions most commonly measured in its center so that it is easier to read and also so that harmonics do not appear. When harmonic indications do appear, they must be distinguished from the primary indication by their height. If this is not possible, a number of readings are taken and the thickness found by substitution into the harmonic formula. If the range is just under a 2:1 ratio, no harmonics of measurements within that range can appear.

The sweep should be as linear as possible; otherwise the calibration marks will be irregularly spaced. In any case the sweep would normally be calibrated against standard samples, *i.e.*, pieces whose thickness was known. Separate calibration marks must be provided for different metals whenever the velocity of ultrasonic propagation is different. Calibration can also be carried out electronically, by feeding a signal of the proper frequency into the unit and noting where the beat falls.

**Magnetostrictive Resonance System.** A resonance measuring system that illustrates many of the characteristics of all similar systems is shown in Fig. 5-11.[1] This happens to be a magnetostrictive instrument, but there is no real difference between it and crystal ones, except in detail.

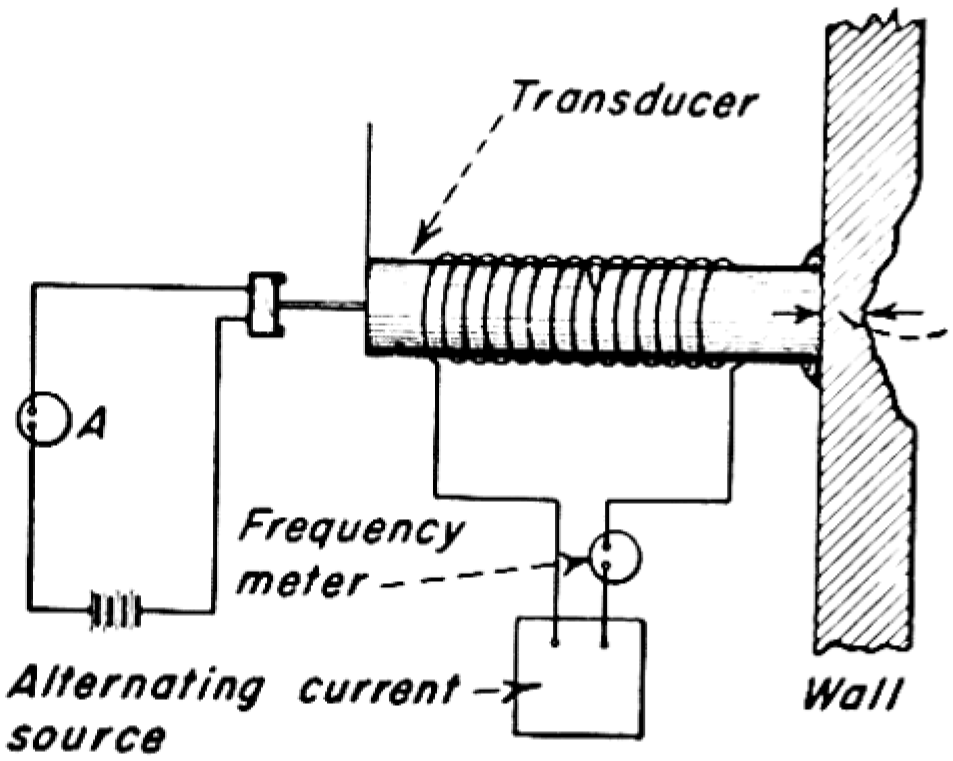

FIG. 5-11. Magnetostrictive system.

The operation of the unit is as follows: A rod or bar of suitable magnetostrictive material is either placed against or permanently fastened to a medium whose thickness is to be measured. Separate readings are naturally taken at those different sections where the thickness variation may be of interest. A coil is set around the bar in the usual manner; and when this coil is magnetized by passing a current through it, the rod is affected according to the magnetostriction effect. It will therefore oscillate at the exciting frequency and will transmit the vibrations into the medium under test.

The frequency of oscillation may then be varied over a range until a resonant condition results. In the figure a special indicator is used. This is a microphone which is mounted on the magnetostriction rod and connected across a metering circuit. The current flow through the microphone will then change at resonance, and the thickness of the wall can be calculated from the frequency indicated.

The velocity of ultrasonics in the medium must be known in advance in order to determine the wavelength. The formula for thickness then is (according to the inventor)

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[1] H. C. Hayes, U.S. Patent 2,105,479, January, 1938.

$$t = \frac{c}{2f - L}$$

where $c$ = velocity
$f$ = frequency
$L$ = length of the rod

Any convenient system of units may be used. Only the general principle is indicated here. However, there is no reason except the intrinsic limitations of magnetostriction why that phenomenon should not be applied to resonance.

**The Reflectogage.** A more recent instrument for measuring thickness ultrasonically when only one surface is available is the Sperry Reflectogage, which is illustrative of a class of instruments now appearing commercially. The work is set into resonant vibration, and the frequency at which this occurs is automatically indicated. Since this resonant frequency, as already indicated, will be directly related to thickness, the instrument may be and is directly calibrated.

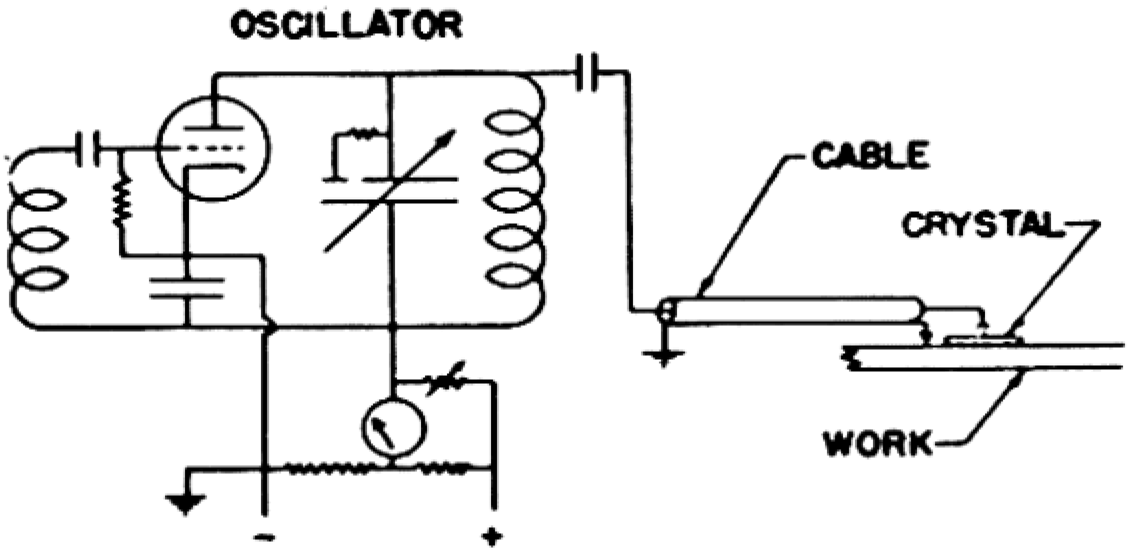

FIG. 5-12. The basic Sonigage.

The Reflectogage is based on the General Motor's Sonigage[1] (Fig. 5-12),[2] which originally consisted of a variable-frequency oscillator and a transducer. The crystal was pressed on the material, and the oscillator tuned until a resonant point was reached. Owing to the losses in the system, power was necessary to maintain the vibrations and was drawn from the oscillator. An output meter was used to indicate the frequency at which minimum power was drawn from the oscillator.

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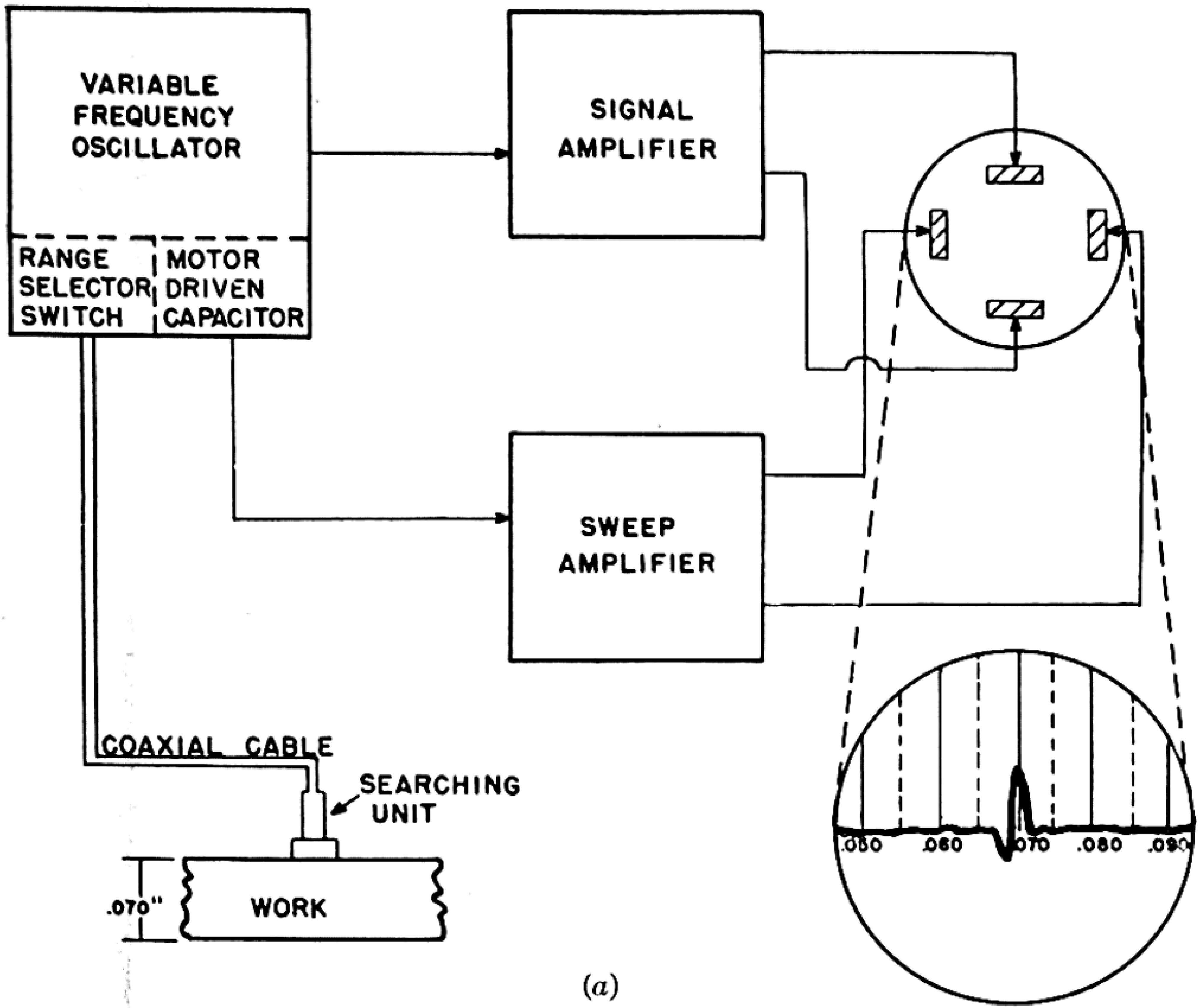
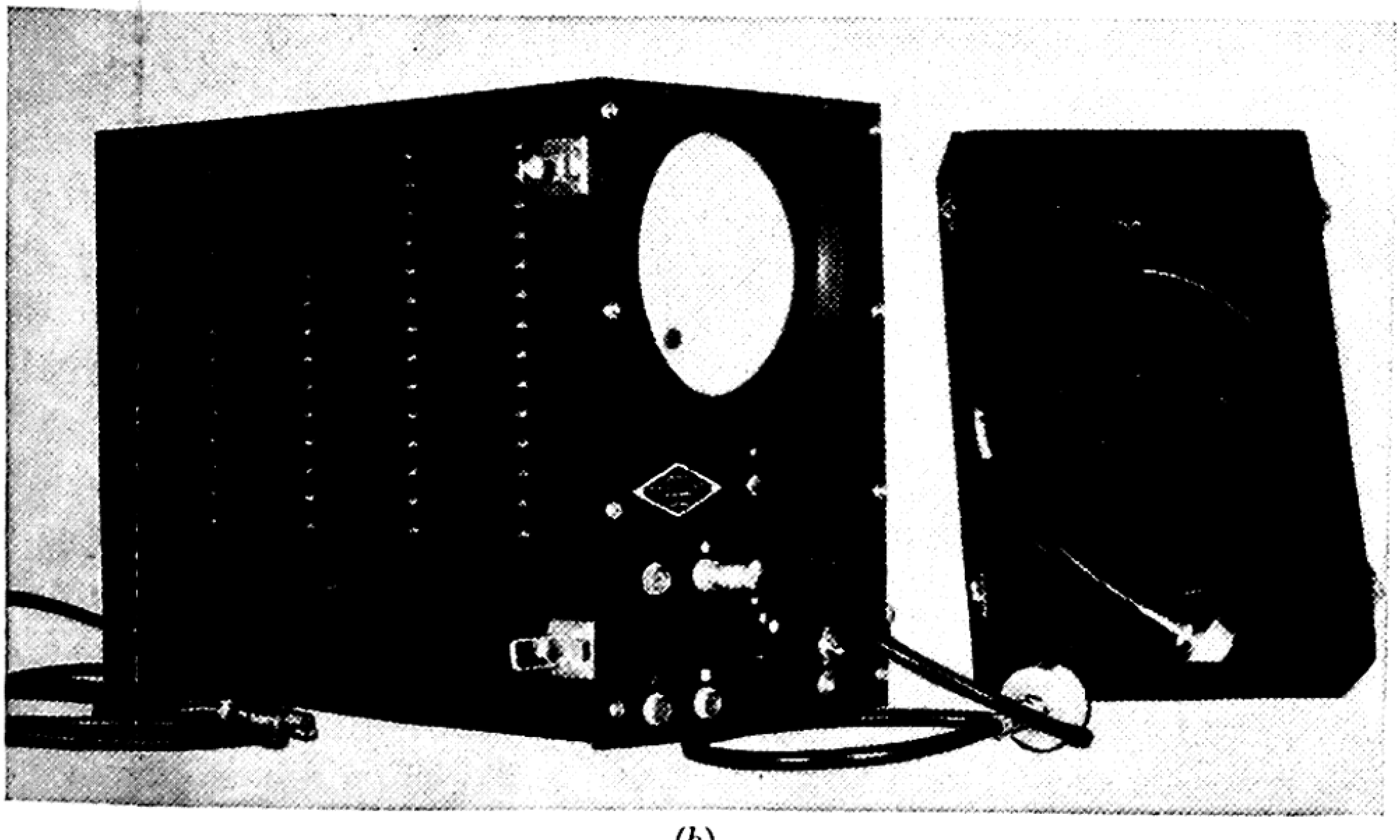
[1] W. S. Erwin and G. M. Rassweiler, The Automatic Sonigage, *Iron Age*, July 24, 1947.

[2] W. S. Erwin, Supersonic Measurement of Metal Thickness, *S.A.E. Journal*, March, 1945.



(*a*)



(*b*)

FIG. 5-13. The Reflectogage: (*a*) block diagram, (*b*) photograph.

Specifically, the oscillator was a one-tube variable-frequency one, with a d-c milliameter in its plate circuit. A sharp change in the current indicated resonance.

Inasmuch as crystals are resonant at their own natural frequencies, the transducers are always chosen with a resonant frequency higher than any likely to be met in the particular range of measurement, so that the oscillator must force them to vibrate at its own frequency rather than the natural one of the quartz. In this case the crystal resonance will have little effect. Resonances in the crystal will otherwise indicate in the same way that thicknesses do.

The dial of the instrument was then calibrated to read thickness rather than frequency. The inventor claimed that he could rapidly read the thickness of sections in the range from 0.020 to 0.400 in. with an error of less than 2 per cent.

An instrument of this class will indicate not only the primary resonances but also the harmonics. However, the amplitudes of the successive harmonics are less than that of the fundamental, and they can be recognized by this means. Also, the approximate thickness of the part under measurement is often known, so there is no question of which indication is correct.

The Reflectogage differs from this original prototype, since it is automatic in operation, *i.e.*, the frequency is automatically varied over a given range by a motor-driven rotating condenser and resonances indicated on an oscilloscope (Fig. 5-13). Ranges are so chosen that the thickness of test falls in the center of a range. In this manner only one resonance pip will appear at a time and can be read directly from a calibrated mask. The complete range of harmonics possible is indicated in Fig. 5-14, as well as the manner of choosing a part of it for presentation.

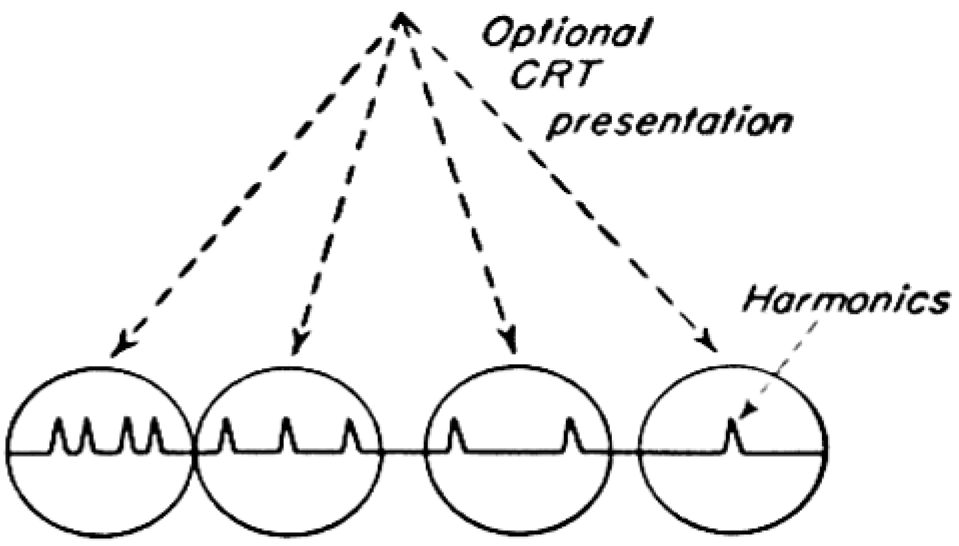


FIG. 5-14. Types of presentation.

Very thick parts can be tested by resonant methods by noting the appearance of the pattern and seeing if there is any gross change as a part is tested. Generally a multiplicity of pips appear on a sweep when this method is used, and the number and spacing of those pips change as the character of the work varies.

**Drop Tests.** Other types of resonant test that are closely related to those already mentioned are the drop and hammer tests, which have been tried with more or less success for a large number of years. Primarily, the procedure for the hammer test was as follows: A mechanic with keen ears tapped the surface of a steel sheet with a hammer and listened for the false note, which indicated to him the presence of a flaw. Unfortunately, such tests were not always successful; but with the advent of sonic and ultrasonic methods, electronic analysis has been applied to them. The system suffers from the obvious defect that the flaw may be a very small portion of the entire tested area and it is therefore difficult to determine when the article is bad and when good. However, although the test has been mainly unsuccessful in use on large parts, it has found a variety of applications in devices designed to test small articles, which can be rung either by dropping them on an anvil or by other means. In most cases the sound is picked up by a microphone or other transducer and analyzed in one way or another.

The basic operation of a drop tester can be analyzed as follows: The article under inspection, which is usually metallic, is dropped on an anvil or struck in such a position that free vibration is possible. Vibrations are set up at a frequency that is generally determined by the structure and dimensions of the material.

In this simplest form the total sound is received on an amplifier whose frequency response can be adjusted so that other sounds than the free vibration of an unflawed piece can pass through it and actuate an indicator. In the more elaborate types complicated frequency-analyzing circuits may be included (Fig. 5-15).[1]

It is sometimes desirable to ensure that the sounds, even if of different frequency, are of the same amplitude so that spurious results are not obtained. Electronic limiters for such purposes are well known in the art. Another means of accomplishing the same object is to ensure uniform drop of the article as far as height and force are concerned. Waves produced in such tests may be either sonic or ultrasonic.

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[1] B. A. Andalikiewicz, *et al.*, U.S. Patent 2,352,880, July, 1944.

Ultrasonic waves have also been produced for other purposes in England by dropping a pellet or hammer on an article in which the waves are to occur.

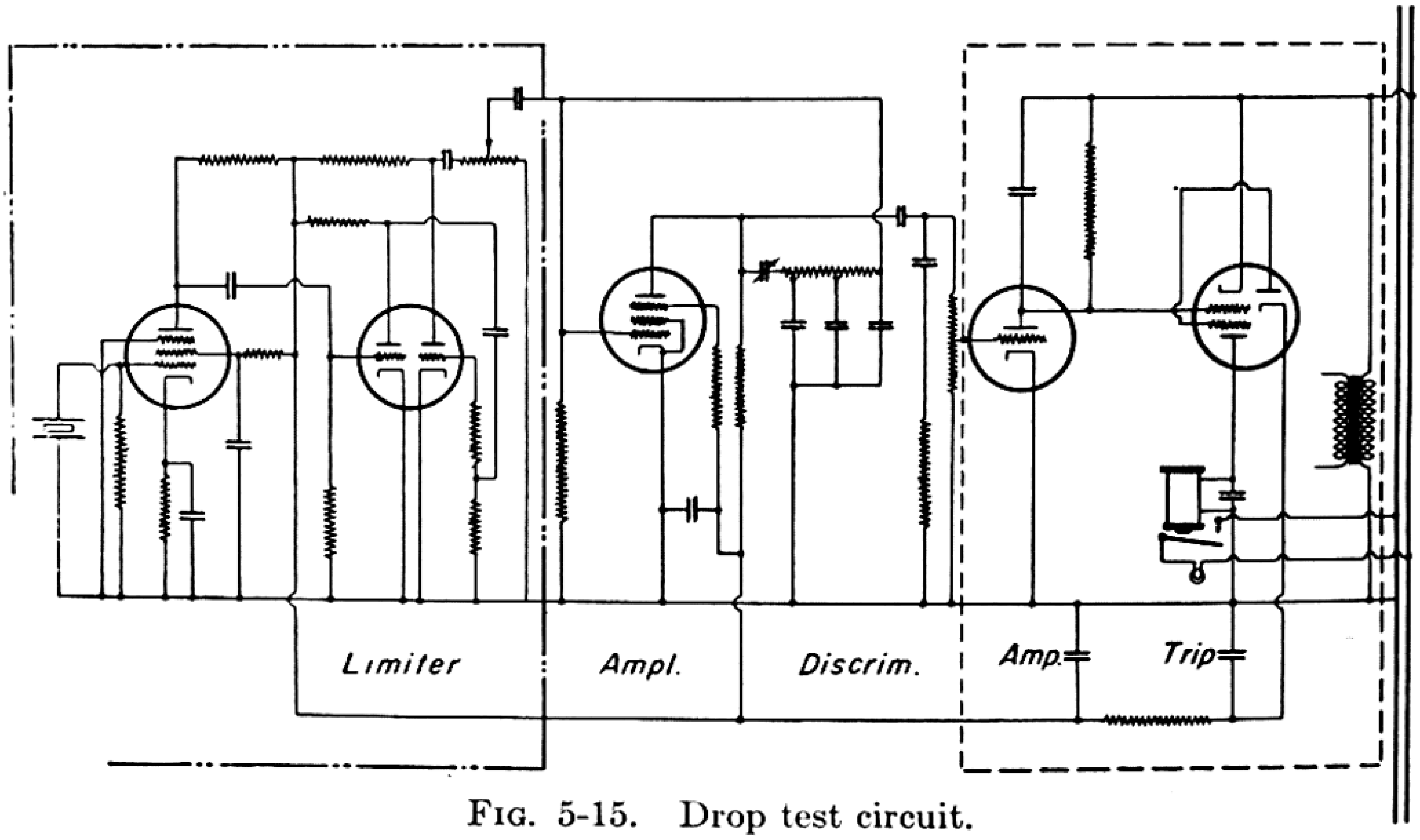

Fig. 5-15. Drop test circuit.

**The Elimination of Standing Waves in Test Systems.** Although it is theoretically possible to match impedances throughout a system so that there are essentially no reflections within it, this is really impossible in practice. The reason for this difficulty is the fact that most ultrasonic systems are not fixed, especially when tests are being carried out, but vary in the relative position of their component parts. Methods have therefore been evolved for reducing the effects of the unavoidable standing waves, especially in continuous ultrasonic systems. Some of those methods are briefly mentioned hereafter.

*Varying Frequency.* Shraiber[1] makes the statement that in his experience standing waves can be avoided only by frequency variations. His reasoning is somewhat as follows: In order to ensure the most efficient transmission of ultrasonics the thickness of the part should be either ½ of the wavelength or a whole number of times as much. Of course, since the thickness is fixed, the frequency can be varied (see Chap. II). Shraiber concluded that a frequency change of about 7 per cent would make a material transmit energy satisfactorily. Of course, this is based on the assumption that all the standing waves exist within the part only and that the transducers are coupled directly to it.

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[1] Shraiber, *op. cit.*

Methods for bringing about changes in frequency over a given range are simple and well known and will be discussed under continuous ultrasonic systems.

It should also be noted that in most ultrasonic systems using continuous transmissions, it is preferable to test in some sort of bath or at least with such an arrangement that the part under test can be moved continuously between transmitting and receiving units, and therefore other resonances must be dealt with, *i.e.*, those in the couplant material, etc.

Rather than vary the frequency of a single oscillator, Shraiber also experimented with using several separate oscillators operating at different frequencies and mixing their output ultrasonically. He claimed some success also with this method.

The author's experience with both these systems is that they are not entirely successful in eliminating troubles from standing waves.

*Other Methods.* Work has also been done in operating at specific angles at which standing waves could not occur. Since the slightest movement of any part of the system, however, changes those angles, such methods are only sometimes satisfactory.

Spaced crystals to cancel standing waves have also been used.[1] Again movement is the big problem. However, the use of spaced crystals was somewhat successful, although it is not so simple as other methods. In such a system both the transmitter and receiver or either one are composed of a group of crystals placed in a holder that holds them a fraction of a wavelength apart, so that they will pick up or transmit, as the case may be, at various points of the standing wave and add up the signals at those points. Such a system could be roughly considered as an integration of signal voltage over a distance. Electrical integration is, of course, not practical, since it would integrate over time and would therefore add bad and good signals.

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[1] B. Carlin, U.S. Patent 2,431,862, Dec. 2, 1947.

Such a system will work because the presence of the standing wave itself indicates perfect transmission and the presence of a flaw would interrupt it. Therefore it is desirable to sum up the variations in the standing wave in order to indicate its presence more exactly. This system is one possible method.

Stepped receivers have also been tried. In such a case the sensitivity of the receiving amplifier may be set to operate an indicator at some discrete step in signal strength; *i.e.*, all signals below a certain strength do not indicate, while all those above it do. This is based on the principle that the standing waves are always present, but always at an amplitude less than that of the real signal. Again, this is questionable. Moreover, the setting of the receiver sensitivity is extremely critical.

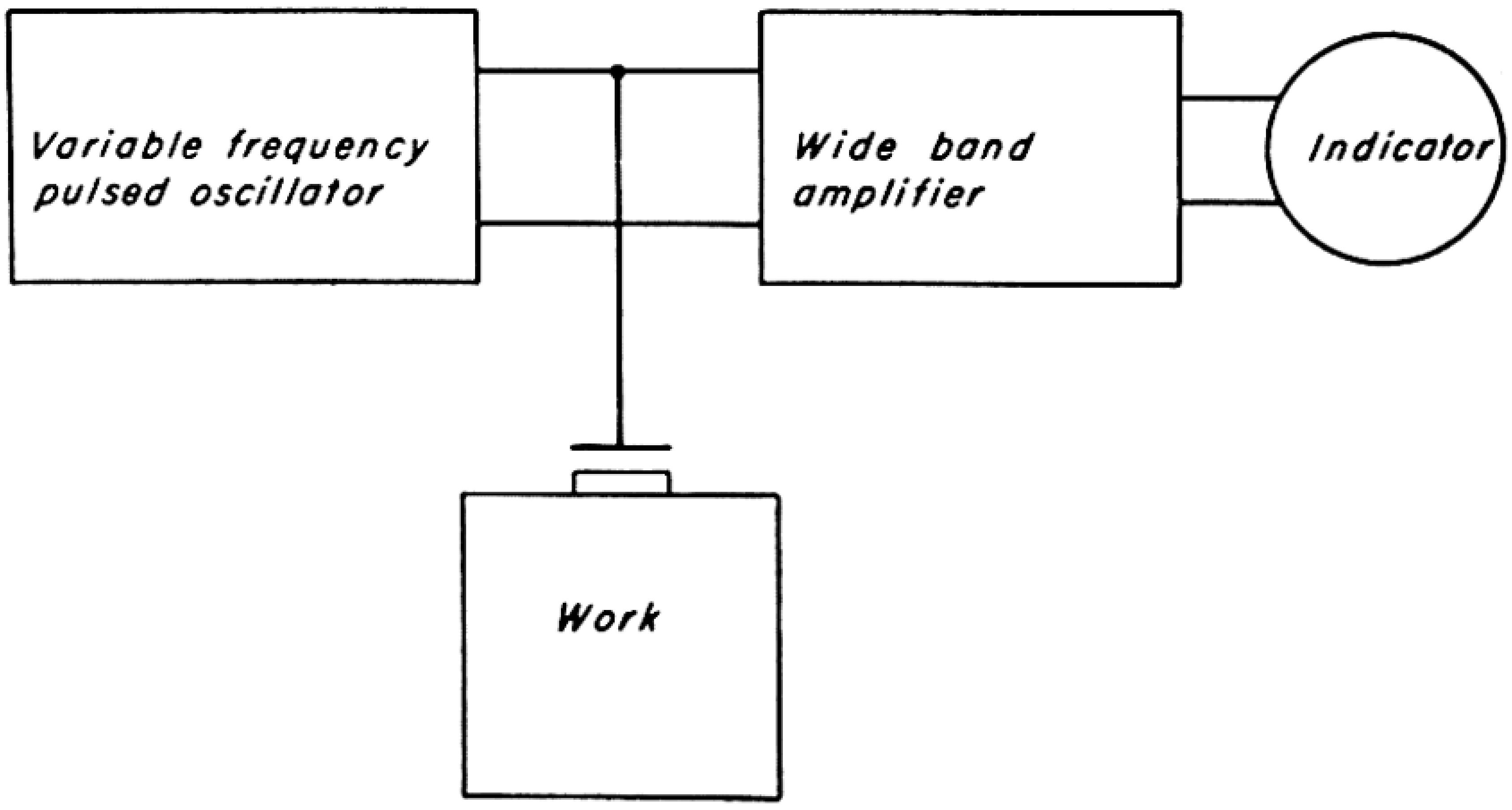

FIG. 5-16. Pulsed system.

Viscous liquids have also been used for more or less the same purpose: to cut down the over-all sensitivity and therefore the standing waves. This has the additional advantage that the first few transmissions have smaller loss than those following. Such a system works on the principle that reflected ultrasonic waves will lose more proportional energy, since they have farther to travel than the simple transmitted ones. Such a system has been used in submarine signaling to cut down back reflections.[1]

*Pulsed Systems.* The most successful means of eliminating standing waves is by use of pulsed systems. Such systems are simple to construct; and since the transmission of energy takes place in short, discrete pulses, there is no time for the standing waves to build up. If there are any standing waves at all, they will occur after the pulse and often can be distinguished from the genuine signal when viewed on an oscilloscope screen.

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[1] Mason, *op. cit.*

A typical pulsed system[1] is shown in Fig. 5-16, and the resulting signals in Fig. 5-17. In this case the initial oscillogram is an exponential pulse viewed directly, the second one shows a nonresonant condition which takes the form of a series of reflections falling closely after each other so that they partially run together, and the last one a resonance condition where the signal bellies out smoothly. Pulsed resonant systems follow all the general laws of resonance.

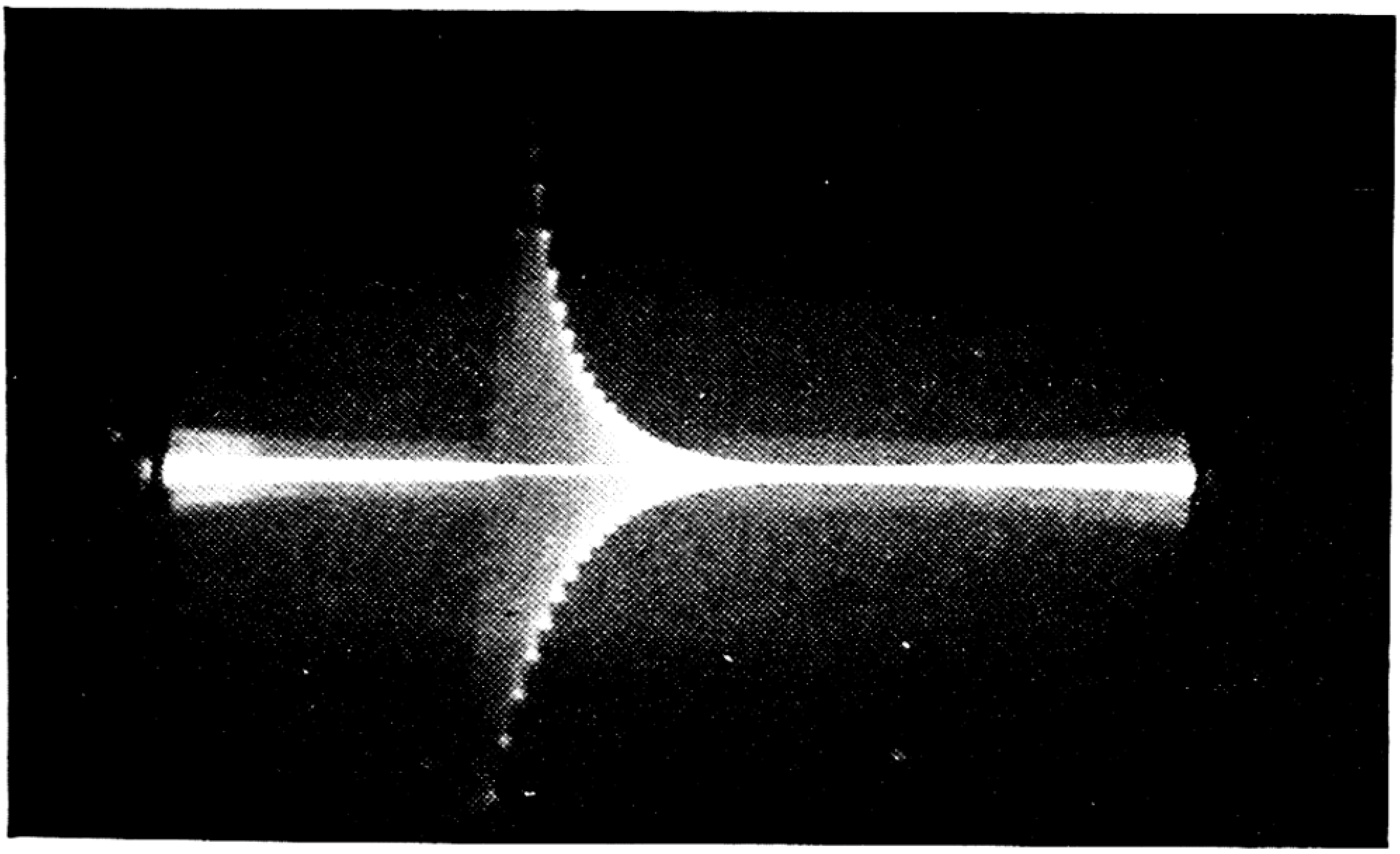
(*a*)

FIG. 5-17. Pulsed resonance indications: (*a*) pulse alone, (*b*) not resonant, (*c*) resonant. (*Fig.* 5-17 (*b*) *and* (*c*) *on following page.*)

**Limitations of Resonance.** Resonance systems work poorly on highly corroded or absorbing surfaces. A very smooth surface without paint or scale is usually required, without excursions of more than a fraction of a thousandth of an inch.

For curved surfaces, curved crystals must be used. Resonance crystals for this purpose are much harder to manufacture than for testing or other purposes.

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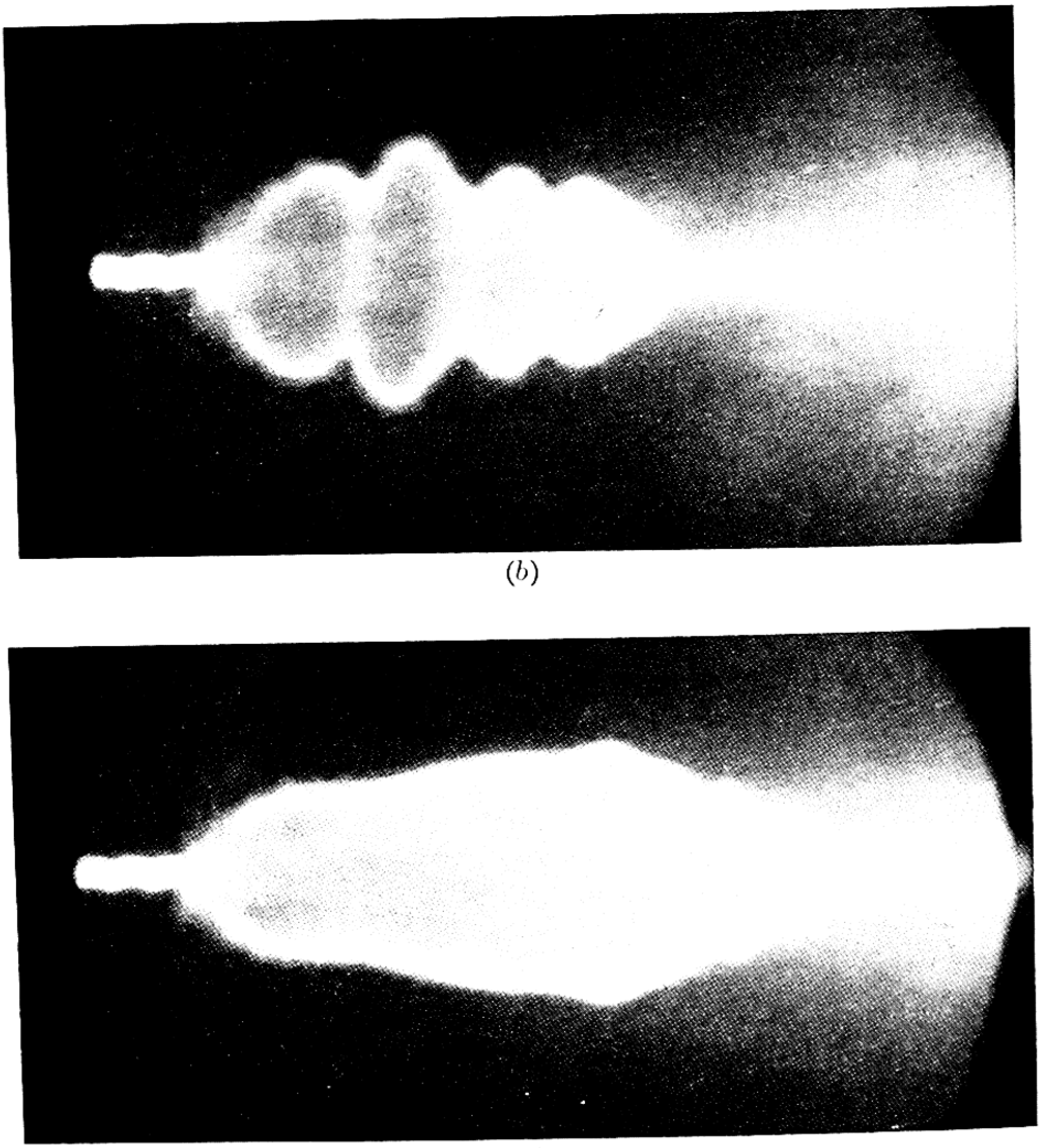
[1] F. A. Firestone, U.S. Patent 2,439,131, April 6, 1948.

Certain types of bonds cannot be tested ultrasonically, since there is always some adhesion, although the bond itself may be either good or bad.



(*b*)

(*c*)

Fig. 5-17. (*Continued.*)

# CHAPTER VI

## CONTINUOUS-WAVE ULTRASONIC SYSTEMS

Continuous waves are defined as those oscillations which are produced and transmitted without any interruption (pulsing) in the time dimension or any modulation change whatever, either in amplitude or frequency. In other words, in this type of ultrasonic propagation every separate wave is exactly like the wave that precedes or follows it. There is therefore no means of distinguishing one alternation from any other.

The transmission and reception of continuous ultrasonic waves were probably used in the first applications of ultrasonics. Many investigators in Germany, Russia, and other countries attempted to apply this phenomenon to their problems of signaling or test.

Certain difficulties have arisen with the use of such vibrations in their purest form, and as a result different types of waves have been used, *i.e.*, ones whose duration was continuous but which had modulation of various types impressed on them. These effects will also be discussed in this chapter, since they are important to the problem. The single case of pulsed systems, *i.e.*, those which send out a discrete number of waves preceded and followed by no oscillation whatever, will be discussed elsewhere, since this is one of the most important systems now used.

**Continuous Waves.** *Testing Materials.* The original experiments with the use of ultrasonics for testing materials seem to have been carried out by Muhlhauser,[1] and his experiments and extensions and variations on them have been repeated by various other investigators. The wide application of his method has, however, been hampered by certain basic difficulties, which have already been indicated and are not easily solved.

*History.* The publication of the Muhlhauser patent in 1933 disclosed the use of ultrasonic energy for the location of various

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[1] Muhlhauser, German Patent 569,598, Feb. 4, 1933.

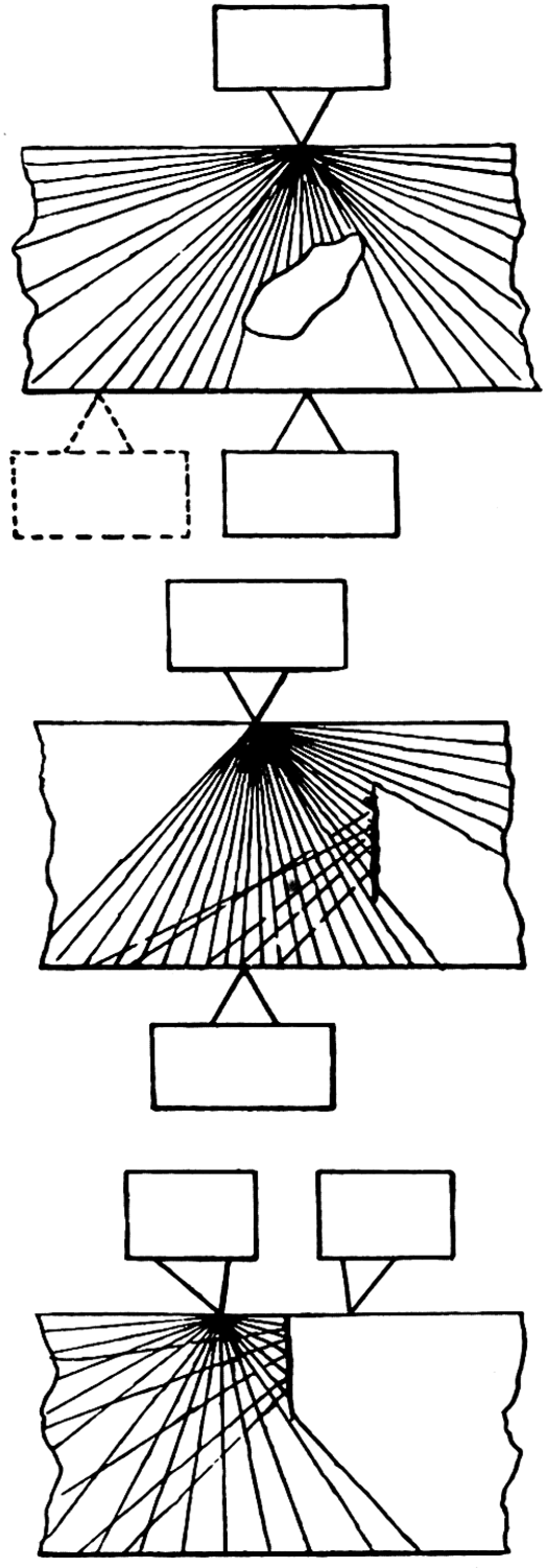

FIG. 6-1. Muhlhauser's methods of testing materials.

types of defects within solid media. The basic disclosure of the patent is the transmission of ultrasonic energy into a part at one point and the reception of the energy at another after it has traveled in the part. The interpretation of the differences in energy level at various points on the material therefore indicates the presence or absence of included flaws.

Figure 6-1 is the drawing of the patent disclosure and represents several possible placements of the ultrasonic transducers. In the first case they are directly opposite each other, and the presence of a flaw in the material between them entirely interrupts the flow of ultrasonic energy from one to the other. In the second case, although there is no flaw directly between them, a crack normal to their faces and to one side reflects a sufficient amount of the otherwise divergent waves to cause an indication. Third and last, the presence or absence of reflected energy is noted. In every case except the first there is obviously some energy transmission at all times. The function of the system is therefore to discriminate among different energy levels and on this basis indicate whether the material is flawed or not.

Experiments carried out with these types of transmission indicate very strongly that the most promising method of test is the first, and as a matter of fact the change in energy level transmitted in either of the other setups is indistinguishable because it is so slight compared with the amplitude of the over-all signal. These arrangements are therefore rarely used in practice.

The general conception revealed in this patent is basic to all similar methods of testing materials. In each of these systems a transmitter and receiver for ultrasonic waves are used, and the ultrasonic vibrations are transmitted into the part, pass through it, and are picked off its surface by another transducer at a point other than the one at which they were introduced. These waves will therefore be affected by any inhomogeneity in the material, and it is this effect which is to be indicated.

Block diagrams of this type of system, with the transducer in direct contact and also with a liquid used as a coupling means between the medium and the ultrasonic transducer, are shown in

Figs. 6-2 and 6-3. The general method is the same in either case. However, the addition of the liquid bath rather than a film of couplant introduces several serious problems.

Muhlhauser used films of coupling liquids in his experiments. However, the first use of thin film of oil for that purpose as well as the first use of liquid in comparatively large bodies as a couplant seems to have been made by Sokolov.[1] His experimental arrangement, with which he carried out work on masses of metal, particularly steel, is shown in Fig. 6-4. The operation was as follows: The transmitting crystal was placed against the work with the usual thin film of oil at the interface. Instead of using

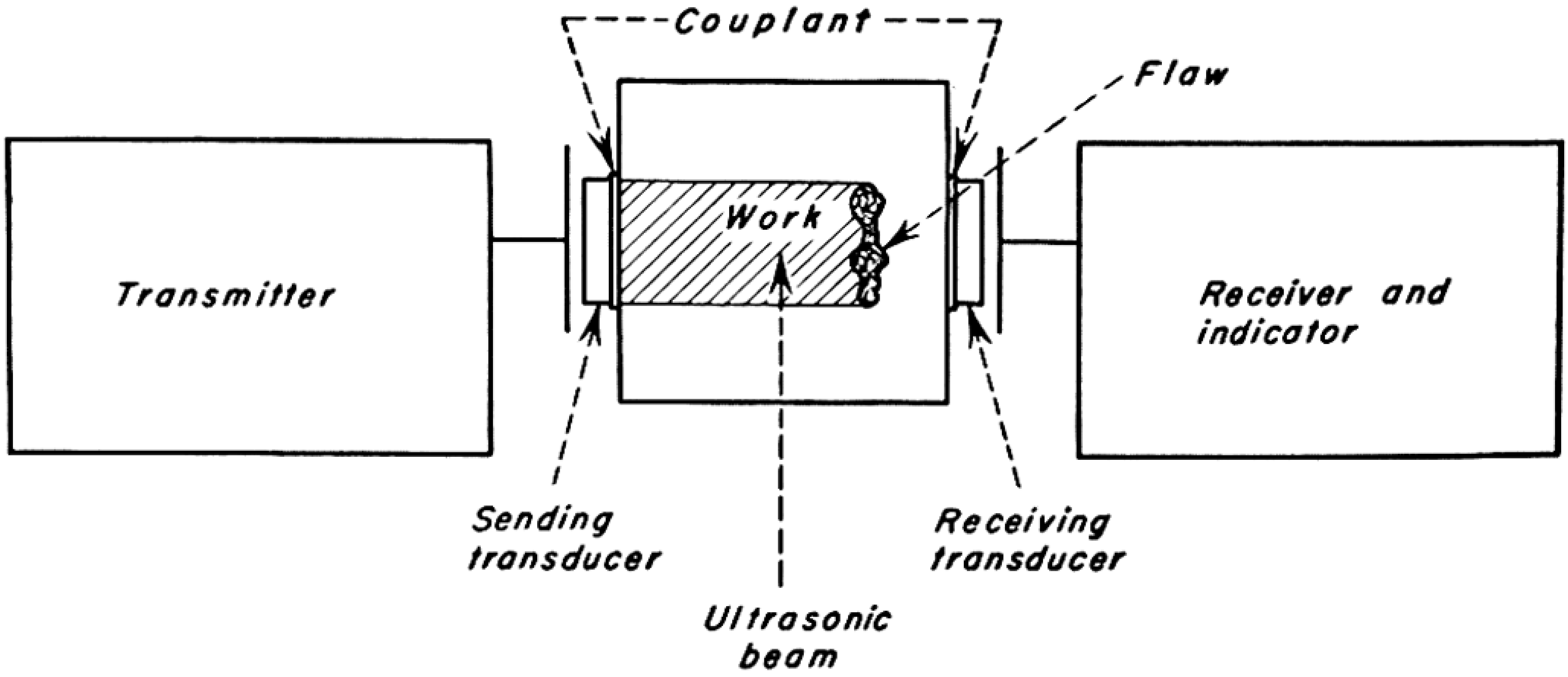

FIG. 6-2. Testing, direct contact.

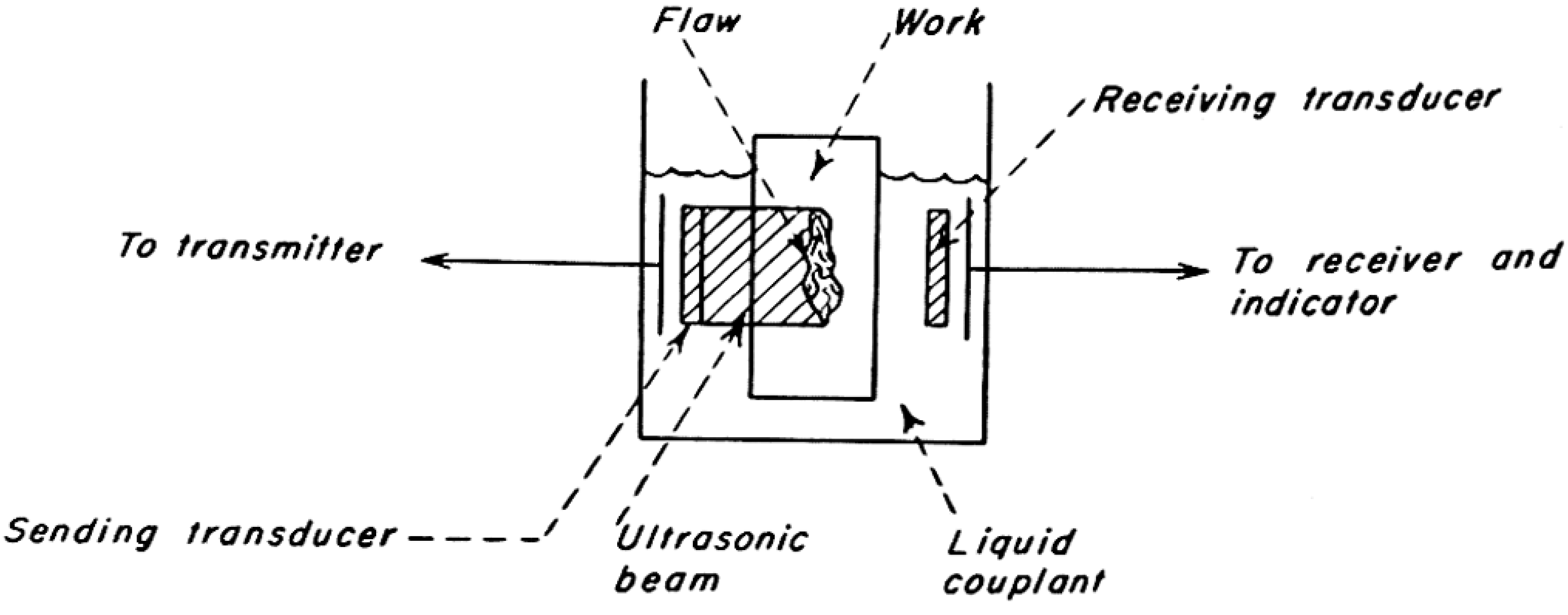

FIG. 6-3. Liquid contact.

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[1] S. J. Sokolov, Practical Applications of the Diffraction of Light on Supersonic Waves, *Physik. Z.*, **36**, 142 (1935).

a second crystal as a receiver, he placed a vessel of liquid against the medium. The ultrasonic waves therefore entered this liquid after passing through the material under test. An optical system was used to project an illuminated slit onto a screen through the liquid in the vessel. Diffraction patterns were therefore produced because of the Debye-Sears effect. These patterns varied with the signal strength. If the material under test were good, one type of pattern was produced, while another type resulted from flawed material.

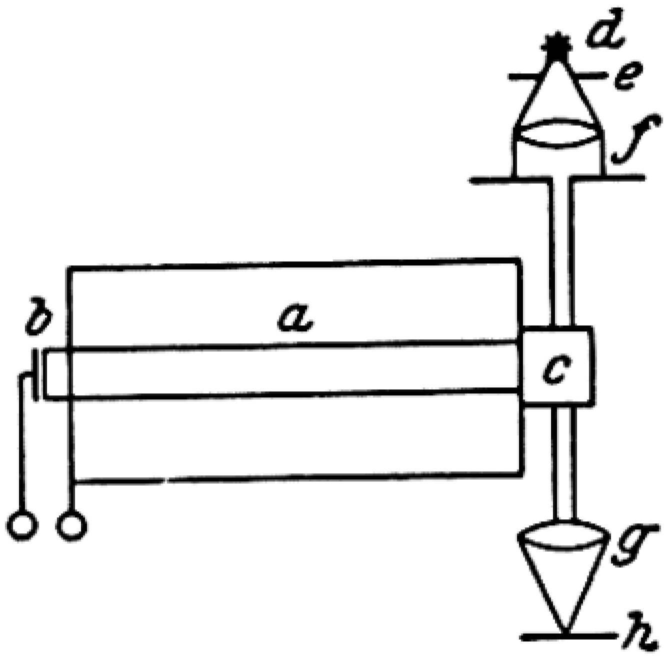

Fig. 6-4. Indicating method: (*a*) medium, (*b*) crystal, (*c*) liquid-filled tank, (*d*) light, (*e*) slit, (*f*) lens, (*g*) lens, (*h*) viewing screen.

Sokolov investigated the amount of couplant that was necessary and found that thin films were sufficient for very flat materials. However, where there was some irregularity of surface, he had more success with mercury, which more nearly matched the impedance at the interface and therefore caused less reflection.

Sokolov[1] also had another arrangement in which the ultrasonic waves passed through a liquid, through the medium under test, and then through a liquid again. He claimed that with variations of this basic arrangement he could rapidly test large amounts of material.

He therefore contributed the idea of a couplant that matches impedance and experimented with different indicators and frequencies. His work was of great importance in the pioneering of ultrasonic testing, and many of the problems originally recognized in his work are still awaiting final solution.

Another of Sokolov's contributions to the art was a mechanism for getting an actual image of the flaw (Fig. 6-5).[2] This is described as operating on the following principle: The ultrasonic energy is transmitted through the part under test and received by a quartz crystal. However, this crystal does not integrate the electric charges produced, which remain isolated on its face.

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[1] S. J. Sokolov, "Ultrasonic Oscillations and Their Application," Electro Technical Institute, Leningrad, June 25, 1935.

[2] S. J. Sokolov, U.S. Patent 2,164,125.

The face is then scanned either by a mechanical contactor or by electron beam.

The operation of the scanning mechanism is synchronized with a suitable indicator such as a cathode-ray tube, which indicates on its face, by intensity modulation, a picture of the state of the sample. The picture on the tube face would therefore superficially resemble an X-ray film.

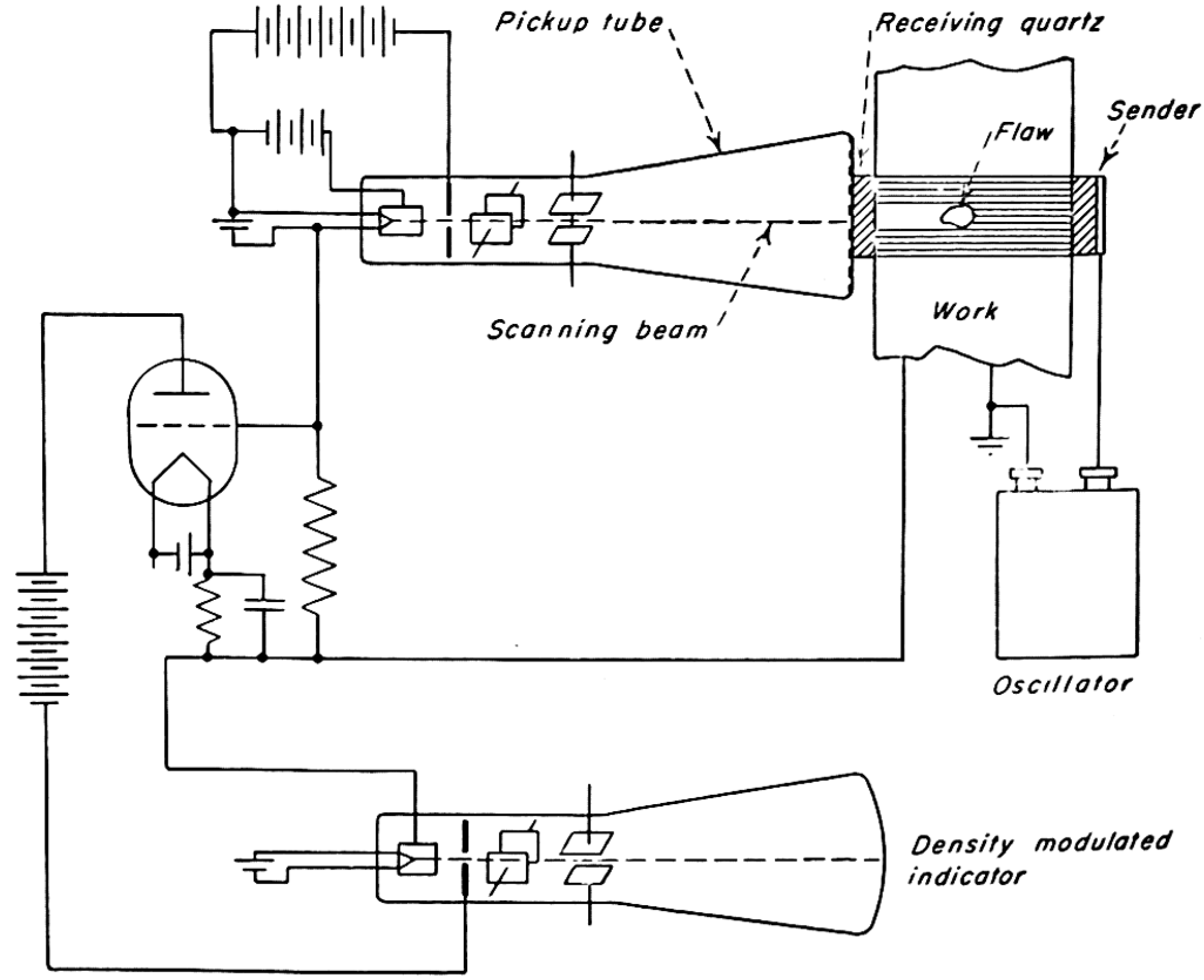

FIG. 6-5. Image system.

This patent is extremely important in that it is the first United States patent granted for this type of ultrasonic testing. Figure 6-6 shows Sokolov's method of scanning mechanically.

Various other systems have been suggested for obtaining an ultrasonic picture of an entire piece but have not been successfully applied in this country to date. However, such systems may have been tried with worth-while results elsewhere. The pictures obtained give ultrasonic testing a slight similarity to

X-ray but are not intrinsically of great value to the growth of ultrasonic testing itself.

Shraiber also contributed a great deal to the art of continuous-wave testing.[1] Among other things, he experimented with testing metals in oil, dust pictures of the ultrasonic beam, diffraction patterns, various types of transducers, a stepped sensitivity receiver, interruption of the beam by a nonconductor, etc. He built units that were used on airplane propeller blades and contained means for recording results on photosensitive papers by light.

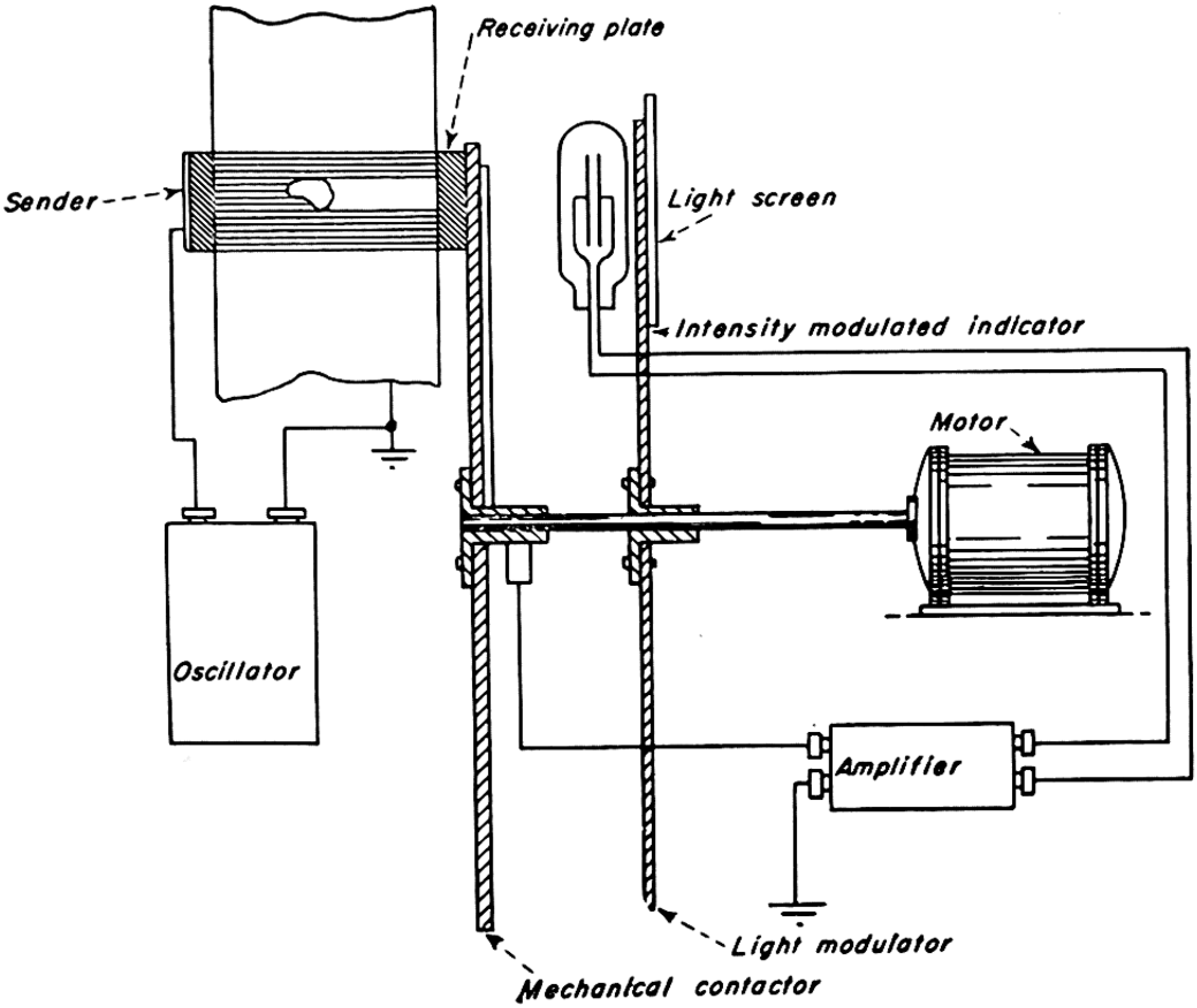

FIG. 6-6. Mechanical image system.

In one of these instruments, which is typical of them all, the oscillator and receiver were set up on rails over a long tank through which the propeller blades progressed. The transducers were mounted on long, waterproof cables and could be conveniently positioned by means of rails. Another tank was also provided with means for moving objects in the ultrasonic beam for test purposes and was used with samples other than the propellers.

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[1] D. S. Shraiber, Determination of Defects in Metal Articles by the Supersonic Method, All Union Institute of Aviation Materials, *Z. Lab.*, **9**, 1001-1008 (1940).

Shraiber's driving oscillator operated from unrectified a-c voltages, and the signals were received and amplified by a superheterodyne type of receiver. This receiver was stepped in sensitivity so that it would indicate the energy only when it was greater than an arbitrary level. A neon bulb was used as indicator. In order to investigate the possibility of electrical pickup between transmitter and receiver, Shraiber used a piece of nontransmitting material, which was interposed into the ultrasonic beam. This stopped the vibrational energy from passing; but if there was any electrical pickup, it still caused indications (see wave interrupters under crystal holders).

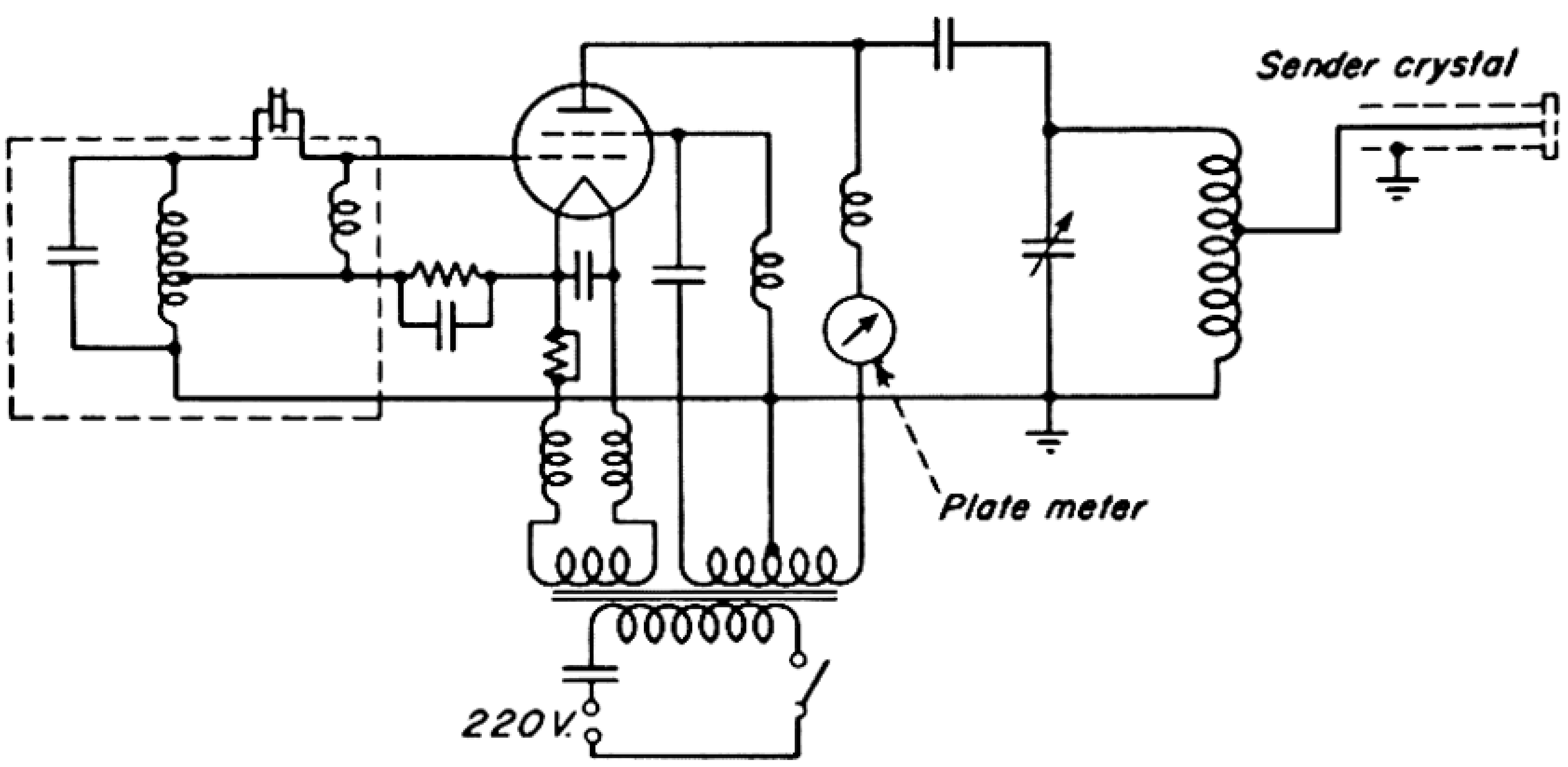

FIG. 6-7. Oscillator used by Shraiber.

Shraiber[1] also mentioned the formation of resonance effects. Figure 6-7 is the schematic of his oscillator, and Fig. 6-8 of one of his receivers. It is interesting to note that the oscillator alone has all the necessary parts for resonance testing, using the plate meter as indicator.

Shraiber quotes the work done by Kruse,[2] who came to the conclusion that it was impossible to test materials ultrasonically, after some experiments with an ultrasonic generator operating between 30 × $10^3$ to 10 × $10^6$ cycles. The energy was sent through mercury, the part under test, and finally picked up by a crystal transducer. A voltmeter was used as an indicator. With this apparatus, the results were so erratic as to be useless. Shraiber analyzed Kruse's difficulty and hit upon the greatest handicap to continuous-wave ultrasonic testing when he concluded that many other factors besides merely the defects in the material influence the ultrasonic intensity of the test beam.

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[1] *Ibid.*

[2] F. Kruse, "On the Testing of Materials by Supersonics," Doctor's Thesis, Hannover Technische Hochschule, 1938.

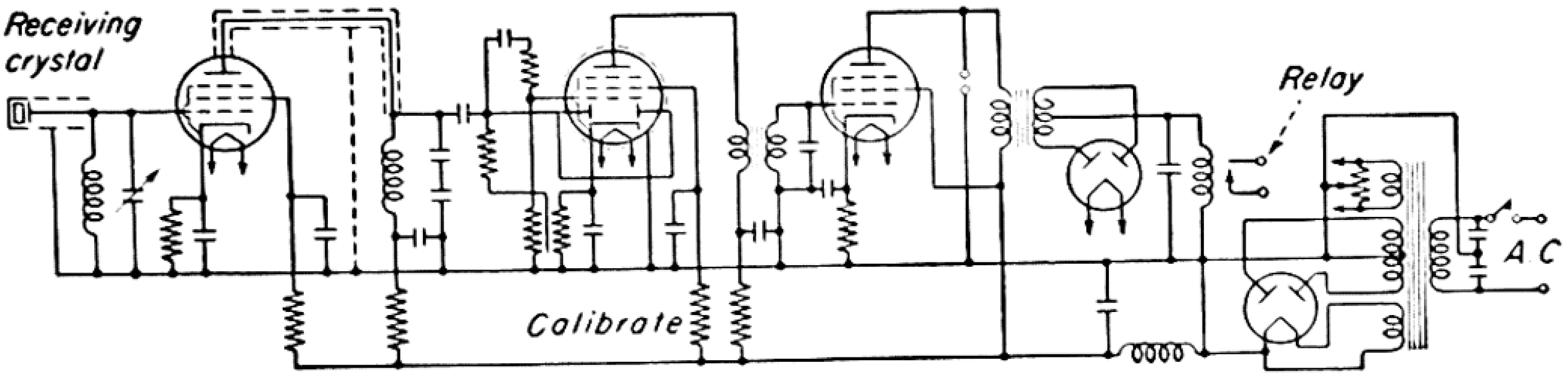


FIG. 6-8. Receiver.

It was Shraiber's idea that these difficulties in interpretation were caused by standing waves, and he therefore suggested the use of stepped sensitivity to eliminate them. These problems are further considered in the chapter on resonance.

Using stepped sensitivity, Shraiber located drilled holes in metal bars with success, as well as very small laminations in similar materials. As long as he confined his work to pieces whose sides were parallel and plane and not less than ½ in. thick, he was fairly successful. With thinner pieces he found himself unable to work consistently.

He therefore began to experiment with a wobbulated frequency in order to avoid the standing waves. He tried both continuously changing the frequency and the simultaneous or alternate transmission of signals of different frequencies. He finally decided that the use of two transducers and two oscillators at different frequencies was most satisfactory.

Shraiber also experimented with lenses and fillers and with the use of spring-mounted transducers that followed the curvature of an irregular part closely.

Figure 6-9 indicates a method of testing a piece by means of metal lenses as suggested by Shraiber. This method promises well theoretically but is difficult to apply. The waves are affected by the lenses in the manner usual in optics.

He also attempted to find a couplant that would have the same velocity for ultrasonic propagation as the common metals. In this connection experiments with oil and lead were carried out unsuccessfully. An analysis of the common liquids indicates that such an ideal couplant does not exist and strong reflections occur between most solids and liquids.

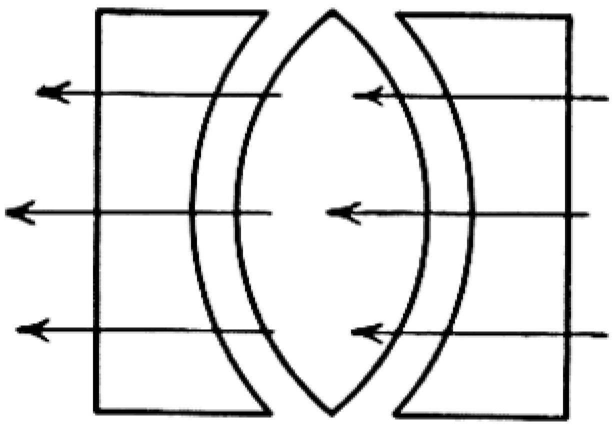


FIG. 6-9. Ultrasonic lens system.

The work of these men laid the foundation for all continuous-wave work. However, although they pointed out certain basic difficulties in ultrasonic testing, they did not entirely resolve them, and these difficulties are still present in continuous-wave testing systems. These difficulties are

1. The generation of standing waves from reflections.
2. The lack of transparency of certain thicknesses of materials to ultrasonics.

**The General Continuous-wave System.** From what has already been said, it may be seen that all ultrasonic systems which use continuous waves are made up of a driving oscillator operating at radio frequency, a receiving amplifier and indicator, and a sending and a receiving transducer. Several of these elements may be combined in one unit, but all are always present.

The medium to be tested is almost always set between the two transducers, usually crystals. A signal from the transmitting oscillator activates one crystal that vibrates and sends a steady stream of ultrasonic energy through a coupling material such as oil into the part under test. This energy is transmitted through that part, passes out of it into and through more coupling material, and activates another crystal transducer mechanically. The receiving crystal transforms the mechanical energy into an electrical one, which is amplified by a vacuum-tube amplifier. It is then impressed on an indicator, which interprets it in terms of whether or not the material is defective.

Almost all units of this nature use a tank of liquid in which to immerse the medium under test. This liquid then acts as a continuous couplant, and the material can be freely moved between the transducers. Most of these systems do not operate on the basis of fine quantitative measurement, but rather on a go or no-go one. The optimum condition is therefore one in which the flaw either interrupts 100 per cent of the ultrasonic beam or allows it all to pass. This, of course, rarely happens, and variations in indicated signal level may then have to be interpreted.

A frequency range of 20 kc to 20 mc may be used. Since the crystal is immersed in a liquid in a holder, it is not subjected to hard wear as in the case of testing by direct contact. It is therefore not critically fragile at higher frequencies. However, most defects in metals may be found within the frequency range from 0.5 to 5 mc. For plastics, wood, glass, and similar materials, frequencies from 100,000 cycles to 1 mc are indicated. Even lower frequencies are used in submarine signaling and communication and usually range from about 20,000 to about 50,000 cycles.

Liquids suitable for application for immersing materials under test may be any of the same ones used as couplants. Oil or water is most common. However, almost any liquid can be used from the point of view of ultrasonic efficiency. A wetting agent such as aerosol should be mixed with the liquid; otherwise bubbles will form and deposit on the face of the crystal. These bubbles can indicate in the same way as flaws.

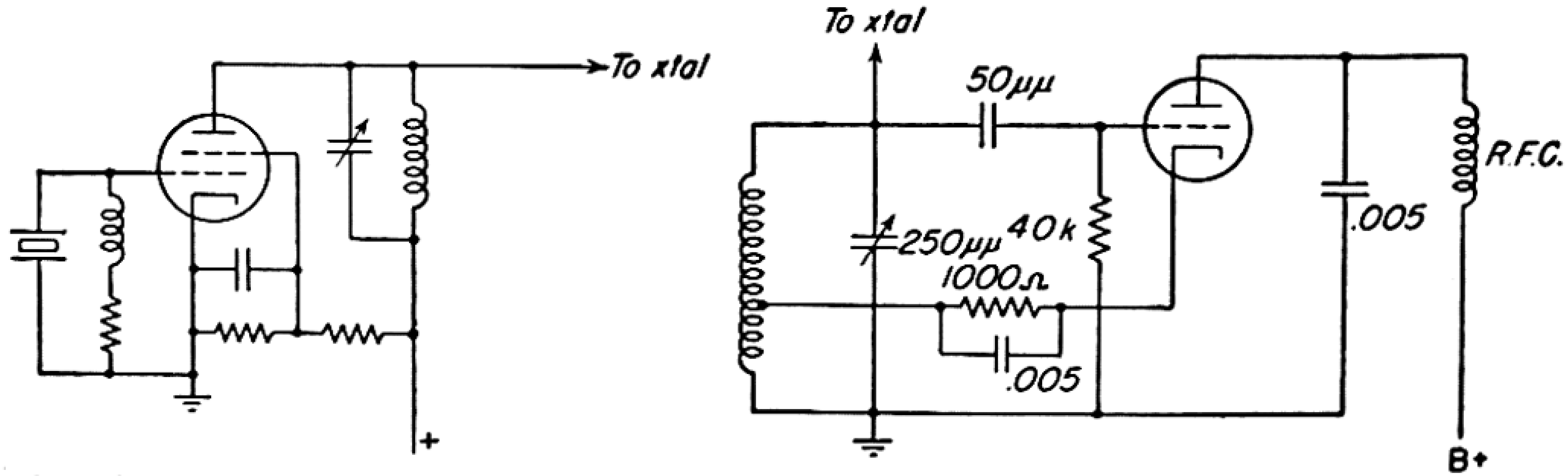
The depth that ultrasonics can penetrate through solids in this type of test is essentially unlimited, and 25 to 30 ft are common in homogeneous media. The energy should, however, be directed normal to any interfaces, since there will otherwise be great reflection and refraction at them.

The movement of the test piece should be regular and if possible should not have any component parallel to the ultrasonic beam, since such a motion will cause the system to act as a sort of ultrasonic interferometer and reflect more heavily at one position than another. Since elimination of this motion is practically impossible unless the part is in direct contact with the transducer, spurious signals almost always result.

One limitation is the temperature of the bath, which should be held within reasonable limits. Another is the fact that certain materials must not be wet because of their own characteristics. Currents in the test tank should be kept to a minimum, since they may affect the readings. This may be done by baffles mounted in the tank.

Even when transmitting into liquids and gases, coupling materials may sometimes be used and are described under crystal holders. In such cases they are almost always solids.

**The Ultrasonic Oscillator.** Almost any type of radio-frequency oscillator similar to those used in electronic work can be used to produce the power for vibrating the crystal transducer. Variable-frequency oscillators are most convenient except in those cases where extreme frequency control is necessary. Crystal-controlled oscillators may then be used. However, the crystal used for control purposes is normally a different one from that used for ultrasonic generation, since the latter is generally too heavily damped to be used as a control device, except in wave generation in gases and possibly in some liquids.



Crystal controlled oscillator

V.F.O.

FIG. 6-10. Simple ultrasonic oscillators.

Although the frequency chosen will depend to some extent on the particular application, it should be continuously variable in the vicinity of the resonant crystal frequency so that it can be tuned to compensate for changes in the system, *e.g.*, the cable lengths. In many cases the cable capacity is part of the tuned circuit. Oscillators for this purpose are shown in Fig. 6-10.

One-tube oscillators of this type will generate enough power for any ordinary testing use and also for short-range signaling purposes. A typical output would be 1 to 10 watts. The physical layout and construction of such an oscillator is extremely important, since any electrical coupling to the receiver, even if small, will be very troublesome. The type of difficulty can be visualized by considering the possibility of cross beats between the ultrasonically produced and electrical signals. Moreover, the electrical signals themselves may cause the indicators to give misleading readings.

The easiest way to isolate the oscillator is to keep it entirely separate in its own cabinet and with its own power supply. However, this may not be desirable from the point of view of economy, size, and portability. The oscillator can therefore be mounted on the same chassis as the receiver, enclosed in one or more concentric shields. The oscillator can also be constructed on a subchassis isolated from the receiver chassis but mounted physically on it and connected to it at carefully chosen ground points. The power supply, if it is a common one, is decoupled by suitable filters. However, electrical filters should be limited to those absolutely necessary, since many obscure difficulties may arise owing to the filters themselves.

More complicated or higher power oscillators can be used for ultrasonic generation. Such oscillators may give an output from 10 watts up. For test purposes the additional power is not important, although it may be in signaling systems. Such units are made commercially for radio signaling.

Matching the cable into the oscillator is very important. Any of the standard methods of matching can be used. When matching is accomplished, the crystal and cable capacity is no longer so troublesome and increased output results. Matching technique is more fully considered in connection with agitation systems.

The frequency at which the ultrasonic waves are produced is usually that of the crystal resonance, since at this point the signals are greatest. However, this is not always true, and a crystal may be driven at other frequencies. Theoretically, any frequency can be chosen, but they are usually ones below the crystal's resonance point.

**Other Generators.** For purposes other than testing, different types of generators may be used. For signaling applications, whistles are often practical and operate at frequencies just above the hearing range. (Whistles are almost exclusively used for signaling in air or in control devices operating in air.)

Magnetostrictive units are widely used in submarine signaling and are considered separately.

**Ultrasonic Receivers.** Any ordinary radio receiver that covers the required range, such as a standard communications type, can be used as an ultrasonic receiver. Vacuum-tube voltmeters fed by one or two stages of amplification can also be used. The output of the amplifier can be modified to operate suitable means of indication such as a cathode-ray tube, meter, light, or relay.

Since it is the amount of energy that is to be measured, the linearity of the receiver becomes of considerable importance, and steps should be taken to ensure it. Attenuators that allow the linear variation of sensitivity are very convenient.

Variations in signal level may occur very rapidly, *i.e.*, as the material under test is passing through the transducers. The meter or indicator must be able to follow this variation. A quick-acting meter, such as a decibel type, is most often satisfactory. A cathode-ray indicator is preferable from this point of view, but not so satisfactory from that of economy and simplicity.

It is desirable to have the output of the receiver actuate a control device such as a light or relay. This can then be used to control the rejection of the faulty material. When only the signal level is of interest, a circuit (Fig. 6-11) may be used on the output of an ordinary radio in place of the audio system. This circuit is shown fed from the intermediate frequency of a superheterodyne receiver but could just as well be inserted in any type of receiver. The detector output is impressed on a gas trip tube such as a Type 2050, in whose plate circuit there is a relay coil and neon bulb. Whenever the 2050 fires, the neon bulb lights and the relay throws.

The gas tube must then recover quickly after breakdown in order to be ready to fire again at the next indication. In order to accomplish this, alternating current may be used on the plate of the tube or the d-c contact broken by the relay throw, since the tube will recover only when plate voltage is removed.

In the most general case the polarity of indication may naturally be adjusted to be in either direction, but it is more convenient to have the light off and the relay open when the ultrasonic signal is being received. The material is good at that time. When the material is faulty, the beam is interrupted and the light flashes and/or the relay throws to reject the flawed part.

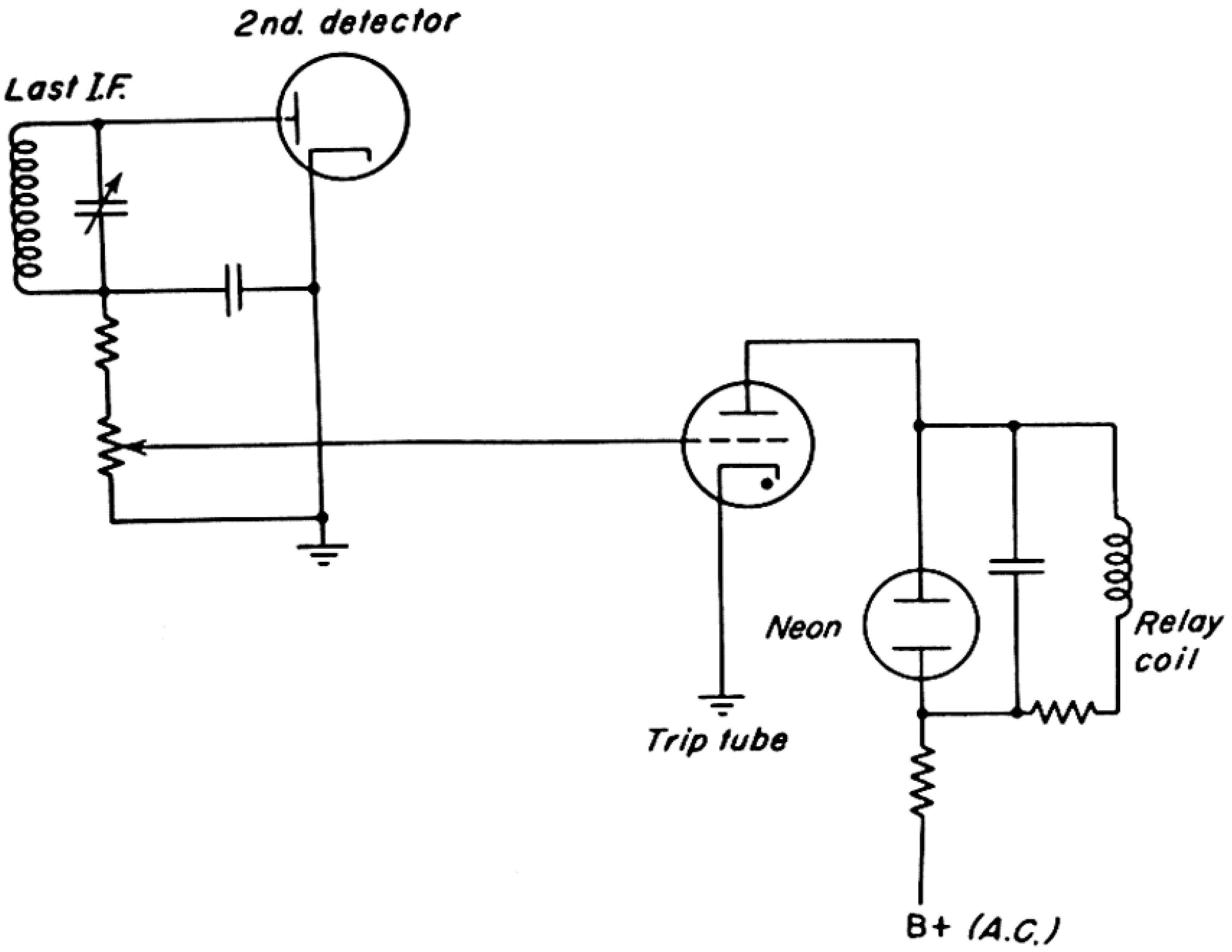


FIG. 6-11. Indicator circuit.

If a meter is desired, it can be inserted in any convenient spot, *e.g.*, as in Fig. 6-12. This meter will then give a quantitative measure of the actual amount of ultrasonic energy received. It may also be used in conjunction with those systems already described, and the trip tube set by a potentiometer in its grid circuit to fire when convenient. In that case it is best to have the meter inserted in such a manner that it will continue to read the amplitude of the signal without reference to whether or not the trip tube has been fired. This system has all the advantages of stepped reception and at the same time gives the actual signal level. The step part of the indication

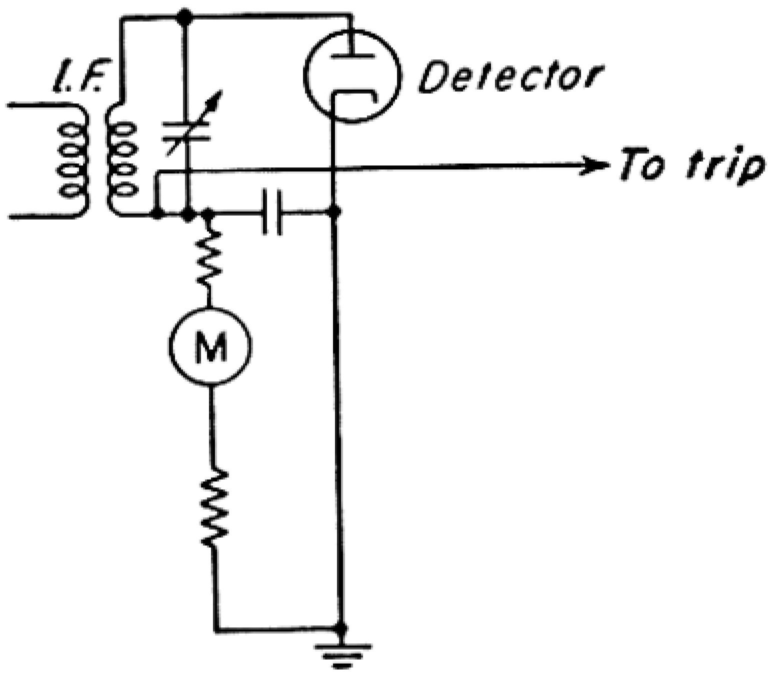


FIG. 6-12. Method of inserting meter.

is, of course, the trip tube. Figure 6-13 is a partial schematic of a superheterodyne receiver suitable for such work.

In short, any good radio receiver with a meter in its output can be used. The band width need not be especially great, since very great resolution is not required.

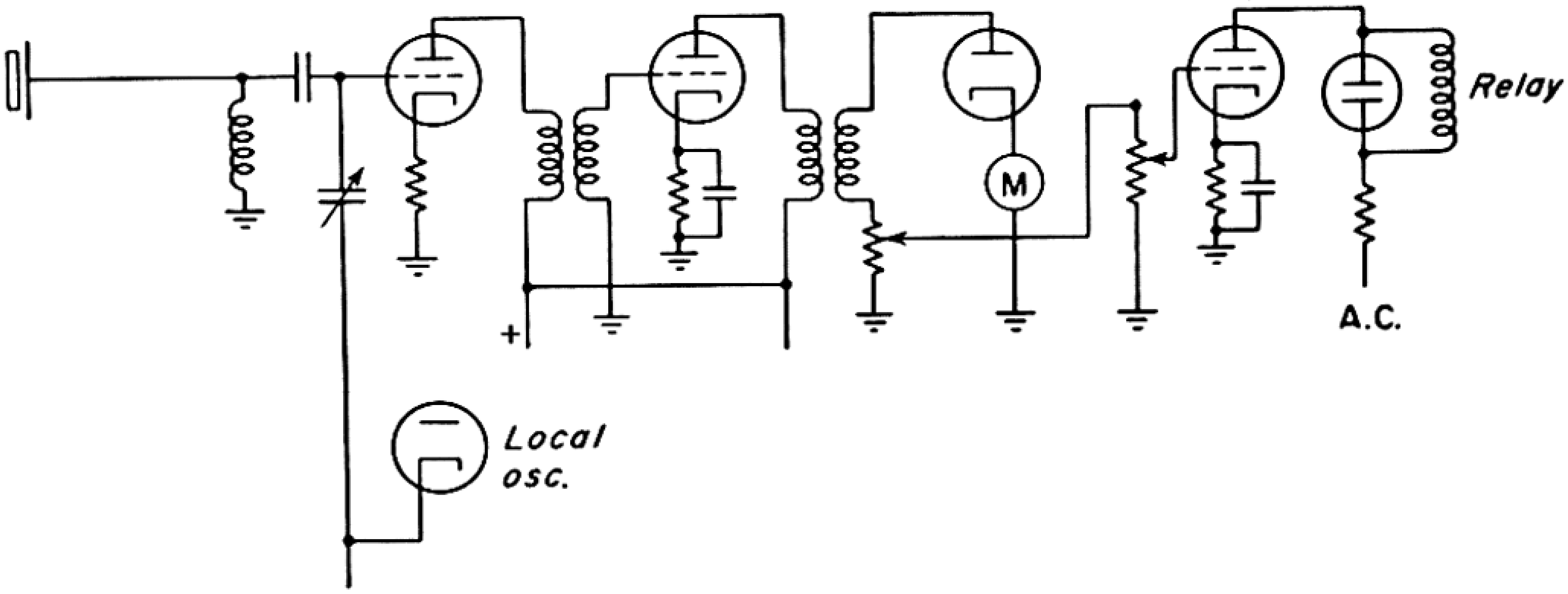


FIG. 6-13. Partial superheterodyne receiver circuit.

Radio-frequency amplifiers can also be used, and one such circuit is shown in Fig. 6-14. This has the same disadvantages of poor selectivity and low gain in this use as in ordinary radio work. However, radio-frequency or video amplifiers have been

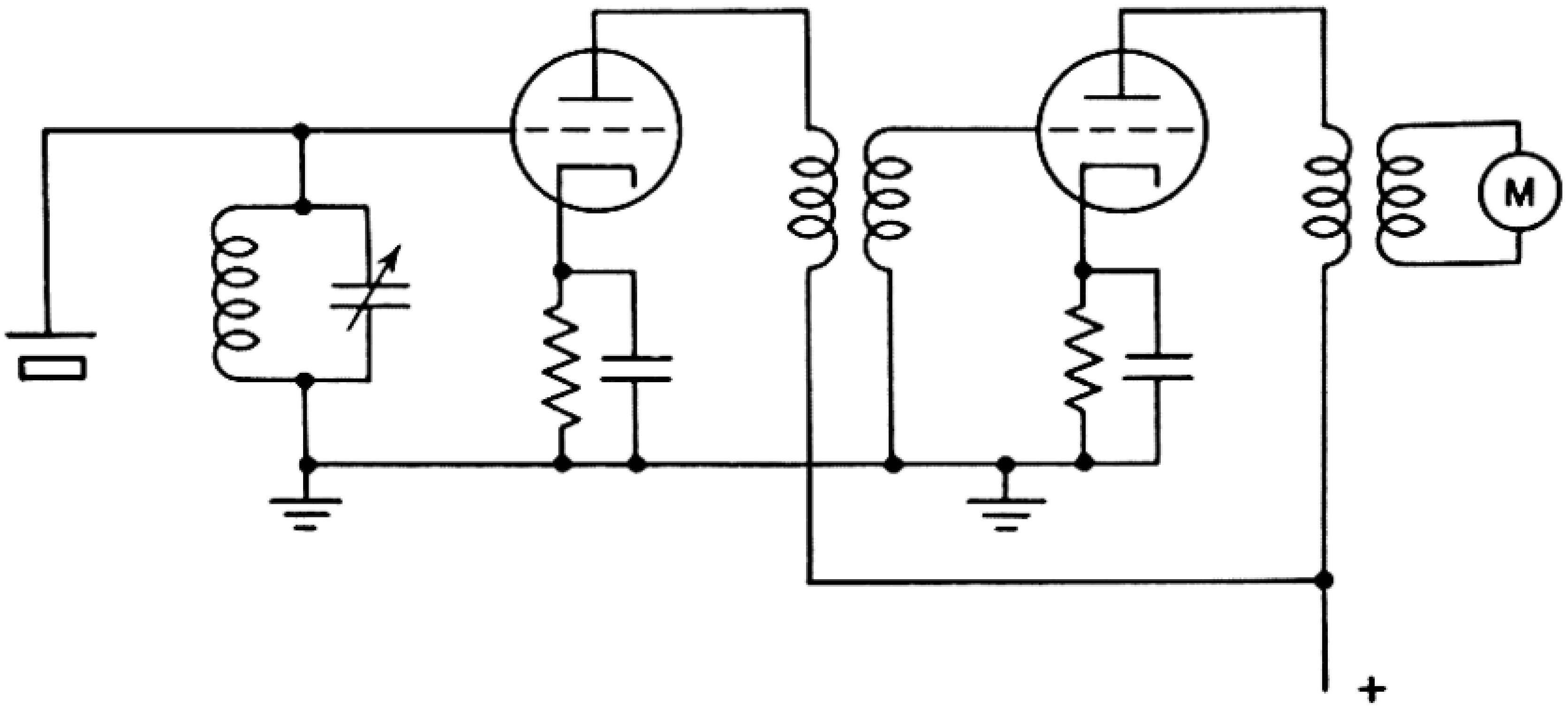


FIG. 6-14. Partial radio-frequency receiver schematic.

successfully used at times. The meter shown is a conventional audio-frequency output type.

Filters are sometimes used in such receivers to discriminate against signals of other than test frequencies. These are designed in the usual way, and their description can be found in radio texts. The presence of such filters is essentially to ensure that only the correct frequencies are feeding through to cause indication.

As mentioned, stepped sensitivity can also be used. In this method the receiver is arranged so that the indicator (relay or neon bulb) throws in at an arbitrary point. The circuits already mentioned can be used for that purpose. This procedure is convenient for production methods, since it gives a very definite and strong indication.

When materials are being tested, the amplifier's sensitivity is set by experiment; *i.e.*, a known sample is introduced into the beam, and the meter set at a standard indication for the flaw. When that is done, the receiver will act in a predetermined manner to reject flaws greater than the sample one. However, it is difficult to calibrate ultrasonic receivers exactly, since so many factors enter into the strength of the signal besides the flaw itself.

Another method of calibrating the receiver is by introducing a standard signal from a signal generator into the input of the receiver. The reading of the output meter or of an independent separate meter located across the output of the receiver will give the receiver's calibration.

This method gives a reading of the receiver's sensitivity, which can then be calibrated against the known flaws. It may be found that the different types of flaws give different indications, *i.e.*, allow different amounts of energy to be indicated in the receiver output.

In ultrasonic signaling in air, the sensitivity of the receiver is not very important, since other factors cause greater changes in its response. These factors are discussed elsewhere. In test work the sensitivity of the receiver is almost always great enough, and a gain of 10,000 is about as much as can be used at present owing to various sources of noise. A receiver of such an order of gain is, however, very satisfactory. Receivers of a gain of a few hundred can sometimes be used in simple systems.

Besides being used for test purposes, ultrasonic amplifiers can obviously be used as control devices,[1] *i.e.*, to operate a mechanism when an ultrasonic signal is either present or absent. Such devices as door openers, counters, etc., can be activated in this

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[1] B. A. Andrews, Ultrasonic Garage Door Opener, *Electronics*, March, 1947.

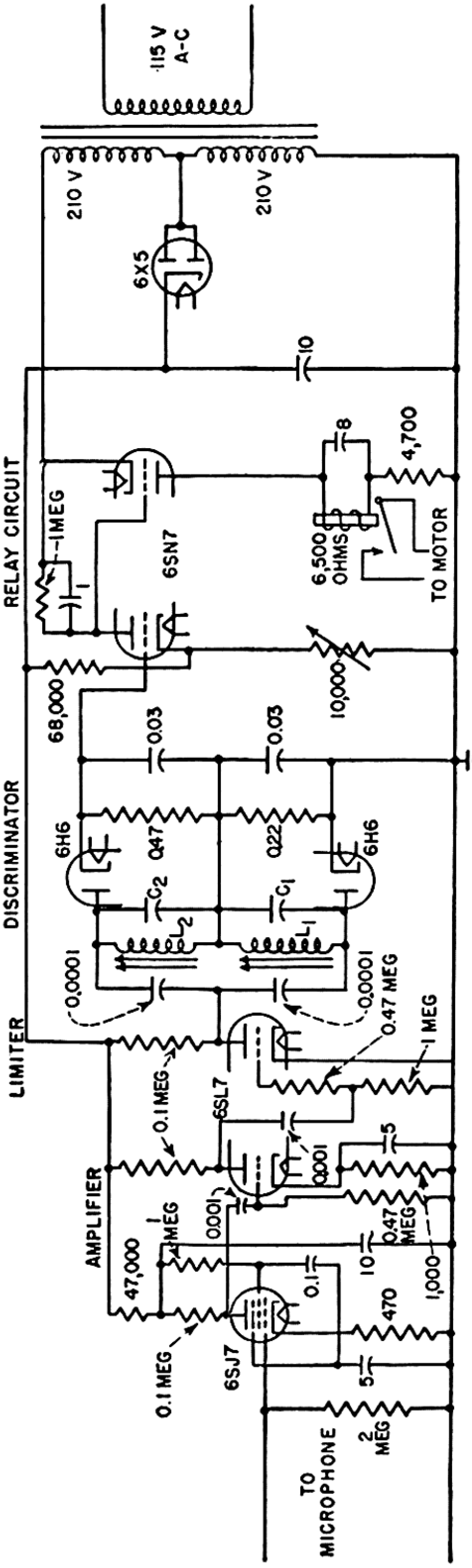

FIG. 6-15. Ultrasonic garage-door opener.

manner. In those cases the receiver should cause a relay to throw at some specific signal level. In some cases the signal is amplified, limited, and then amplified again to introduce into the control circuit a signal that is always constant.

A circuit for this purpose is shown in Fig. 6-15. Any of the amplifiers already discussed can be used thus as a control device. Ultrasonic energy can be used in this manner much as light is used with the photoelectric cell. A whole field of control devices is therefore possible.

**Sonic or Ultrasonic Signaling.** Besides their use for testing purposes, ultrasonic waves can also be used for signaling and ranging. In many of these applications continuous waves are used.

Methods of ultrasonic communication and ranging are of particular concern in wartime, although not of great interest otherwise. The application usually takes two forms, *i.e.*, the transmission of intelligence by modulated ultrasonic waves traveling either in the atmosphere or in the ocean and also the location of objects in the same media, without, however, transmitting intelligence.

**Signaling by Ultrasonic Carriers.** Ultrasonic signaling in the atmosphere is usually carried out at the very low ultrasonic frequencies, *i.e.*, from about 20 to 30 kc. Such frequencies give wavelengths of approximately ½ to 1 in.

Energy for such purposes may be produced by whistles, which can be driven either by the breath or by gas or air blasts. They can also be activated by vacuum.

Unfortunately, there is very great absorption in the atmosphere, as well as other factors that cause a loss in the ultrasonic signals. While all of these factors do influence the amount of transmission, it can be shown that no matter how much power is generated by the whistle, penetration in the atmosphere is limited to very little more than 1,000 ft even when parabolic reflectors are used to concentrate the energy.

**Factors That Control Transmission.** The transmission is influenced by many factors, chief among which are atmospheric conditions such as temperature, humidity, and wind.

As in other ultrasonic work, frequency of signal also has great influence; and as the frequency becomes higher, the transmitted waves travel shorter distances. At about 20 kc transmission with a given system might be about 200 ft; at 30 kc only about 100 ft would be penetrated. This indicates that the signal frequency should be as low as possible. This is always true where penetration is desired. At very high frequencies, of course, air is an excellent insulator to ultrasonic waves.

Another factor that affects the transmission is the height of the sending transducer above the ground, both because of the line of sight factor and also because of the influence of the ground on the ultrasonic waves that pass over it, especially when there is grass or shrubbery acting to interrupt the energy.

Many other specialized factors cause losses and therefore indirectly limit the transmission. Such factors are the spreading of the energy, molecular effects, shadows or reflections, conduction, damping or viscosity, etc. Most of these are natural limitations, which cannot be compensated for by the signaler.

Ultrasonic signaling is also limited by noise naturally present in the atmosphere that is in the same general frequency range as the signal. This is, however, not so serious as the other factors.

It should be noted that although the transducer itself is not affected by air or water currents in the medium, the ultrasonic waves are, and greatly changed results may be observed when such currents are present.

For all these reasons it is unlikely that the transmission of ultrasonic energy traveling through the atmosphere will be widely used for signal purposes.

**Methods of Use.** The factors already mentioned naturally influence the ultrasonic signals no matter what applications are contemplated. The commonest use is in interrupted code transmission or in modulated systems. Listening systems are also used for location of objects, usually by triangulation, *i.e.*, the use of several listening points with directional receivers, which give a bearing on the source of sounds.

Continuous-wave ultrasonic energy can also be used for object location by means of the Doppler effect. A moving object carrying an ultrasonic generator will produce marked Doppler effects when it approaches a reflecting surface, such as a wall. This type of device can therefore be used as a warning to indicate the proximity of a reflector.

**Signaling in the Ocean.** Most sub-ocean signaling is pulsed rather than continuous. However, continuous-wave listening is widely used in ocean warfare, and elaborate listening systems, consisting of banks of transducers of highly directional types, have accordingly been developed.

Telephoning on a sub-ocean carrier, though possible, has never been widely used, although Langevin contemplated it as one of the major applications of ultrasonics.

**Tuning the Transducers.** All continuous-wave systems in common use are equipped with two crystals, one for sending and another for receiving. In such cases it is extremely important that the two crystals be tuned to exactly the same frequency, since the resonance curve of quartz is extremely sharp; *i.e.*, a slight mistuning of one crystal will cause a sharp decrease in signal strength. It is very unlikely that two crystals of the same nominal frequency would be precisely the same, since there are usually differences in grinding or mounting, which may cause slight variations. Moreover, one or both crystals may be changed during the life of the instrument, and mismatch may occur in that way.

For these and other reasons both crystals are usually tuned in some way. This can be done in various manners: either by a condenser in series or parallel with the crystal or by movement of one of the crystal electrodes where that is possible. A series condenser is the simplest expedient for accomplishing the tuning.

Variation in the electrode distance is not ordinarily used because it is critical and difficult to accomplish and requires a more complicated holder and because crystals are usually plated by evaporation or deposit, thereby making the electrodes incapable of movement.

**Transmission at an Angle.** The continuous-wave method is sometimes used with the search units on the same side of a part. Such a method was disclosed by Muhlhauser and is illustrated in Fig. 6-16. The success of such a test depends on the spread of the beam of ultrasonic energy. Some of the energy travels at an angle that is determined by the beam spread and is reflected in a specular manner. It thus travels along in a direction essentially parallel to the front face of the transducer until it hits a flaw or reaches the receiver. This method is, however, not too successful, since the angle of travel is not sharp enough.

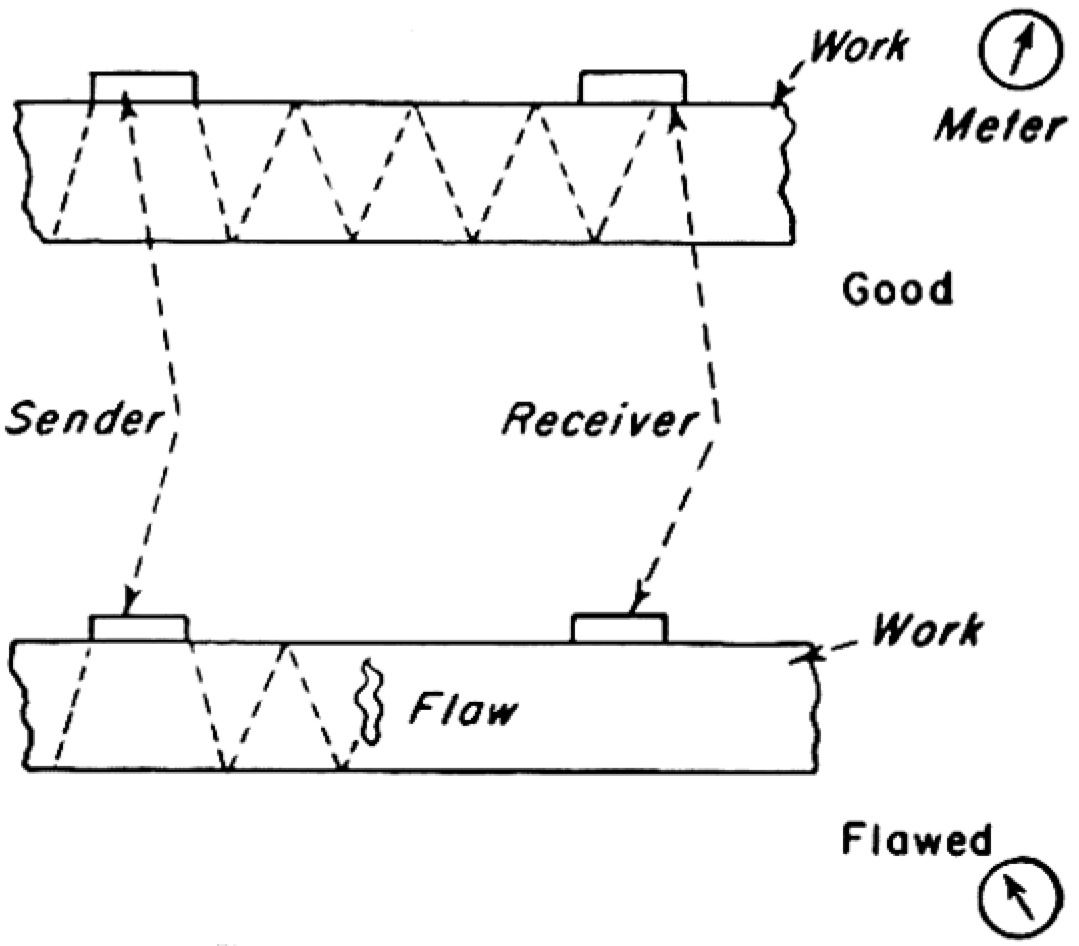

FIG. 6-16. Test method.

Bez-Bardili[1] experimented with solid plates at an angle to the ultrasonic beam in a liquid and from this found certain angles at which there was greater transmission than at others; *i.e.*, he drew a relationship between angle of incidence and amount of transmission of the ultrasonics. An arrangement for introducing ultrasonics at an angle is shown in Fig. 6-17. Such angular introduction can obviously be used for test or other purposes.

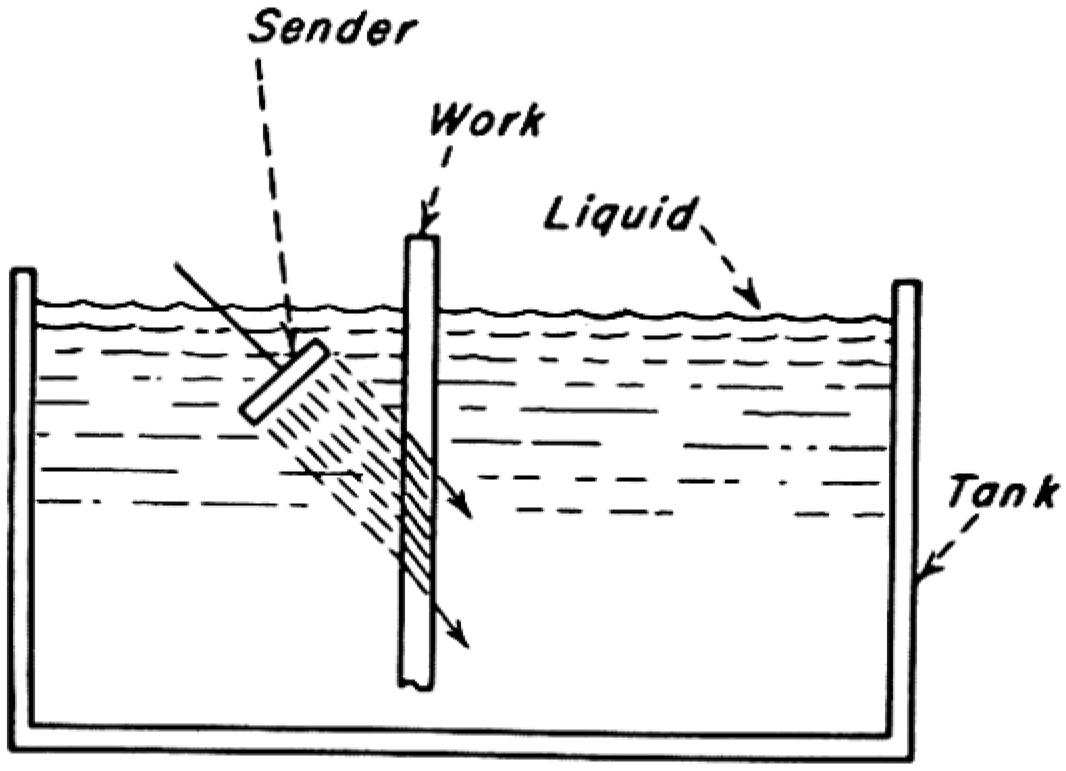

FIG. 6-17. Angular introduction of energy.

This technique would be valuable for introducing ultrasonics into a curved surface or one on which it would be difficult to place the crystal. Angles may be chosen that will give optimum transmission, and such angles would be valuable for testing materials in a liquid bath.

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[1] W. Bez-Bardili, *Z. Physik.*, **96**, 761 (1935).

**Some Experiences with Continuous-wave Testing.** A series of investigations with continuous-wave apparatus was undertaken to explore the possibilities of application to the testing of materials. The procedure may be of some value in establishing such programs.

A tank was set up as shown in Fig. 4-18, and rails provided for mounting the transducers so that they could be positioned as desired at various distances and angles. Flat sides were formed on the crystal holders to hold them rigidly at a specified position and angle.

For an oscillator a conventional electron-coupled single-tube-type circuit was used, with the crystal connected directly across the tank circuit. The transmitter and receiver were carefully tuned, and it was established that there was no electrical pickup. This was done by interrupting the ultrasonic beam and turning the receiver gain high. Any indication was interpreted as pickup.

A series of tests was run on both flat and curved materials, both with and without a beam-limiting device. The results were very similar except that they were somewhat less obscure with the baffle in place. This undoubtedly had the desired result of keeping some of the reflected waves from setting up standing-wave combinations. It may also have had the effect of preventing currents from forming in the liquid.

In the cases of both flat and curved sections slight movements of any of the fixed physical dimensions caused a marked difference in signal level, as indicated on an output meter. Although the receiver was not absolutely linear and therefore showed a tendency to overload at the upper amplitudes, there was still a wide range of linear operation indicated within narrow limits.

It appears clear from these experiments that the interference effects with ordinary continuous waves, *i.e.*, without any special features, are so serious that the method cannot be used except in the case of gross defects, such as those which substantially interrupt the entire beam. There are large numbers of false indications and no way of telling these indications from genuine ones except by a great number of tests, which may enable the experimenter to determine, on the basis of the repeatability of his results, whether a particular indication represents a flaw or not.

In the case where the cross section of the flaw was large enough to interrupt the entire beam, consistent and clear results were found, and it appeared that continuous-wave methods were most successfully applied to it.

**Standing Waves.** It has been indicated in much of the early experimentation that standing waves caused great variation in indication. That is particularly true in continuous-wave systems. Numerous methods of avoiding these effects have been tried, both in the medium and in the couplant, but in most cases without success. These methods are extensively considered under resonance.

Many ways of absorbing the energy have been suggested or patented. All types of absorbing materials have been used.

One means of attenuating the energy is the use of gratings or screens with castor oil introduced as a viscous agent[1] to add attenuation. This patent also mentions the use of a metal wool, which adds greatly to the absorption of the energy.

Any of these methods can be used. Generally the attenuating agent is introduced behind the receiving crystal, so that reflections do not bounce about in the tank and change the signal level.

**Varying the Oscillator Frequency.** Any of the usual methods of varying oscillator frequency can be used. However, the simplest method is to connect the rotor of the frequency-controlling condenser to a motor that will rotate it and therefore periodically change the frequency. Motors with ratings of 1/75 hp are satisfactory. In most cases the bearings of the condenser must be changed for such service, and provision made for shock mounting the tubes to prevent microphonics. The condenser plates must also be dynamically balanced to obtain a smooth-running system.

Frequency modulation by electronic means is also possible, and means for doing this will be found in the literature.

In the case of a rotating condenser, great difficulty is experienced in making satisfactory contact with the rotor and in eliminating hash caused by poor contacts. When electronic modulation is used, care must be taken to prevent drift.

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[1] W. P. Mason, U.S. Patent 2,415,832, Feb. 18, 1947.

In order to avoid these difficulties the simultaneous transmission of several different frequencies may be resorted to. In such a case several oscillators operating independently provide the range in frequency necessary to avoid standing waves. The same result can be accomplished by switching the different frequencies alternately rather than impressing them on the crystal simultaneously.

As indicated, filters[1] may be incorporated in the receiver or amplifier so that only the range of frequencies being used will be indicated. This is especially necessary where the range used is of the same frequency as extraneous sounds, *i.e.*, in the audible range or near it.

**Other Methods of Indication.** As already discussed, the modulation of a light beam can be used to indicate the changes in the amount of ultrasonic energy transmitted in such a system. However, this method is so cumbersome that it is rarely used except in experimental work in a research laboratory.

The amount of agitation on the surface of a pool of liquid can also be used to indicate the emergence of ultrasonic energy. This, too, is a laboratory method.

In Germany several specialized methods were worked out during the war for making the path of the ultrasonic waves visible after they emerged from the part under test. For example, the usual optical projection means were used together with small floating particles, which oriented themselves to provide a more visible signal.[2]

**Shielding.** In continuous-wave ultrasonic systems, especially where the work is entirely immersed in a liquid, it is difficult to get satisfactory electrical isolation. The tank filled with liquid will pick up energy if it is placed near a source of such energy. Conductors, when they are placed in such a tank, will therefore pick up signals that will cause trouble.

Since the signal produced by the ultrasonic energy hitting the crystal will combine with the electrical pickup, extreme care must be taken to shield the apparatus and to ground all parts completely.

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[1] W. E. Morris, U.S. Patent 2,378,237, June 12, 1945.

[2] R. Pohlmann, *Physik. Z.*, **113,** 697 (1939).

# CHAPTER VII

# PULSED ULTRASONIC SYSTEMS

The use of pulsed systems in all types of radiation has contributed greatly to military and civilian developments. As in other forms, pulsed ultrasonic methods are particularly significant.

**History.** Pulsed systems for measuring distances by means of ultrasonic radiation probably were first used in the field of submarine signaling. In 1912 Richardson was granted two patents in the United States for the use of this type of energy to indicate the approach of icebergs.

As already mentioned, Langevin, in France, made a major contribution to the application of ultrasonics to submarine detection when he was able to carry on signaling under water at 0.1 mc. In doing this a condenser microphone was used as transducer. Langevin was also the first to apply the piezoelectric effect to this field in a submarine transmitter, which he constructed for the French government. The vibrating systems used have already been partially described. Each was a mosaic of crystals 2 mm thick, which was pressed between steel plates 25 cm in diameter and 3 mm thick. The whole unit therefore resonated at about 40 kc. The same arrangement is now widely used in both transmitters and receivers by connecting either an oscillator or a receiving amplifier across the transducer.

Generators and receivers of ultrasonic waves were later used extensively in signaling from ship to ship, in locating submerged submarines or sunken bodies, in determining the depth of the water in which a ship was proceeding, and especially in locating hostile submarines in wartime. A great deal of experiment was naturally carried out in Germany, which specialized in submarine warfare.

Considerable work was also done in America, both by the Navy Department and by various private concerns. Professor Fessenden worked along these lines for the location of icebergs in about 1914. Throughout this work the elapsed time of travel method was used, *i.e.*, the measurement of the time between the sending out of a pulse of ultrasonic (or sometimes sonic) energy and the reception of an echo. If the velocity of the wave were known, the total time of travel could be divided by 2 (once coming and once going) and the time for a one-way propagation determined. Once this was known, it was simple to determine the distance traveled.

Similar approaches were used to measure the ocean depth. The general idea of several such systems is shown in Fig. 7-1.

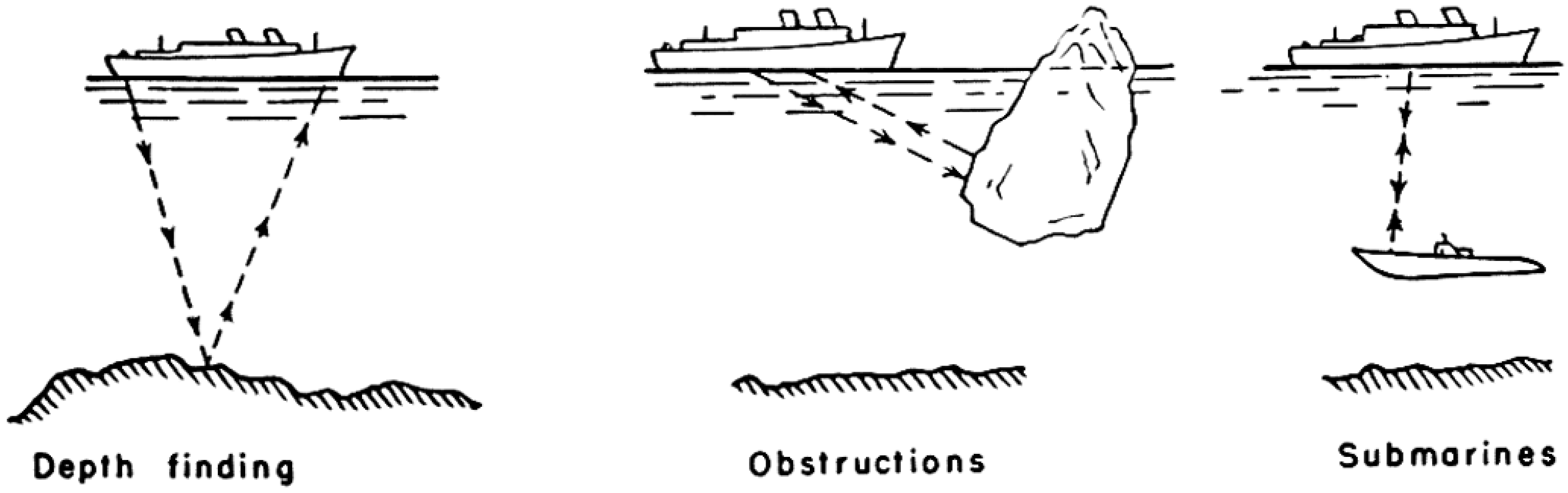

FIG. 7-1. Underwater applications of ultrasonic signaling.

Although these systems worked fairly well at large distances, *i.e.*, in great depths of water, it was much more difficult to measure shorter ones, *i.e.*, smaller intervals of time. Methods for such measurement were crude; and since ultrasonic waves travel at about 4,800 ft/sec in the sea, very small time intervals resulted. As a matter of fact, intervals of 0.1 sec were originally difficult to measure, and the pulse length itself approached or transcended that value.

A fairly recent submarine signaling indicator of the type used will show its basic complexity and the difficulty of making fine measurements of time by such a mechanism (Fig. 7-2).[1]

A number of specialized pulsed systems resulted as experimenters tried to avoid the necessity of small time measurements. One such system was to send out a known number of pulses, spaced at regular intervals. The operator then determined if all the pulses were reflected and heard. This indicated the depth.

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[1] Orlich *et al.*, U.S. Patent 2,384,766, Sept. 11, 1945.

In 1919 the United States Navy tried an angular method of transmission (Fig. 7-1). The sounds (or ultrasonic noises) of the propeller or artificial generator were sent against the bottom of the sea at an angle and picked up at some other point on the ship. Since the shortest distance to the ocean bottom was straight down, this gave the pulses a longer distance to travel; hence longer times elapsed. Unfortunately, experiment proved that the time advantage gained was so slight that the method worked only where perpendicular transmission also did.

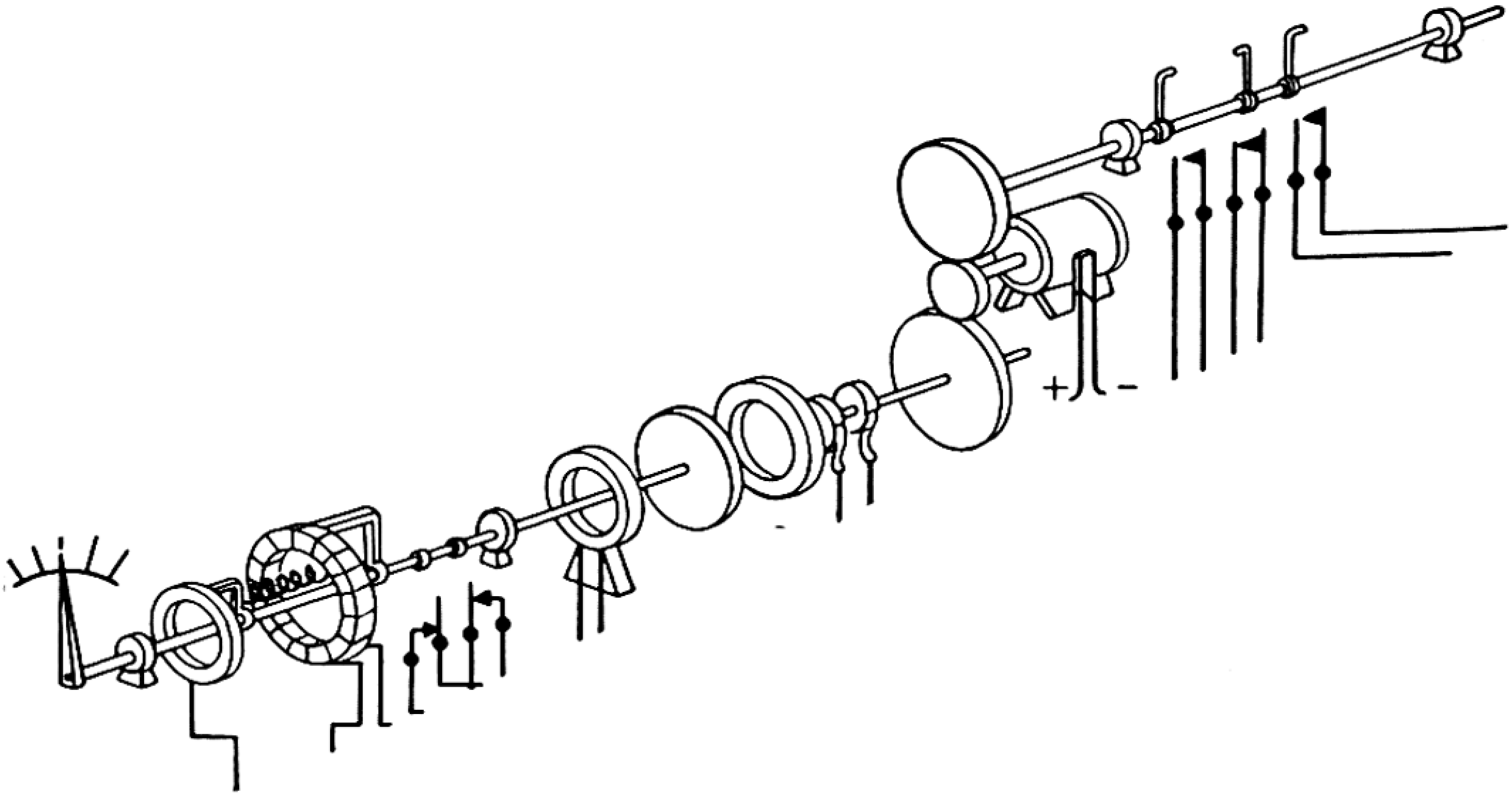

Fig. 7-2. Typical mechanical indicator.

The resonance method already described in connection with a German development was also used. This worked satisfactorily at small depths, but not so well at great ones.

The reflection of a pulse from the sea bottom was used as a trigger for a successive pulse, and the frequency of repetition measured. This was never adopted extensively, as the difficulties were as great as for straight reflection techniques.

Many of these systems have been tried in seismic signaling, radar, and altimeters as well as in submarine work. In many cases the same principles of operation have been adapted to other types of radiation besides ultrasonics.

All these systems are based upon the measurement of the time it takes the ultrasonic pulse to travel in a medium where its velocity is known. The problems intrinsic to the methods are therefore those of measuring small intervals of time. Since the war and during it, many exact and accurate methods of measuring time easily to the nearest millionth of a second (or closer) have been developed. The problem of the measurement of time has accordingly ceased to be such a great one, and the simple pulsed method has therefore steadily gained in use. Systems for accurately measuring time to the nearest fraction of a microsecond will be described in the text.

The similarities between ultrasonic units and those used in radar, seismic exploration, and other fields have already been mentioned. A brief description of the basic methods of those other systems is therefore in order.

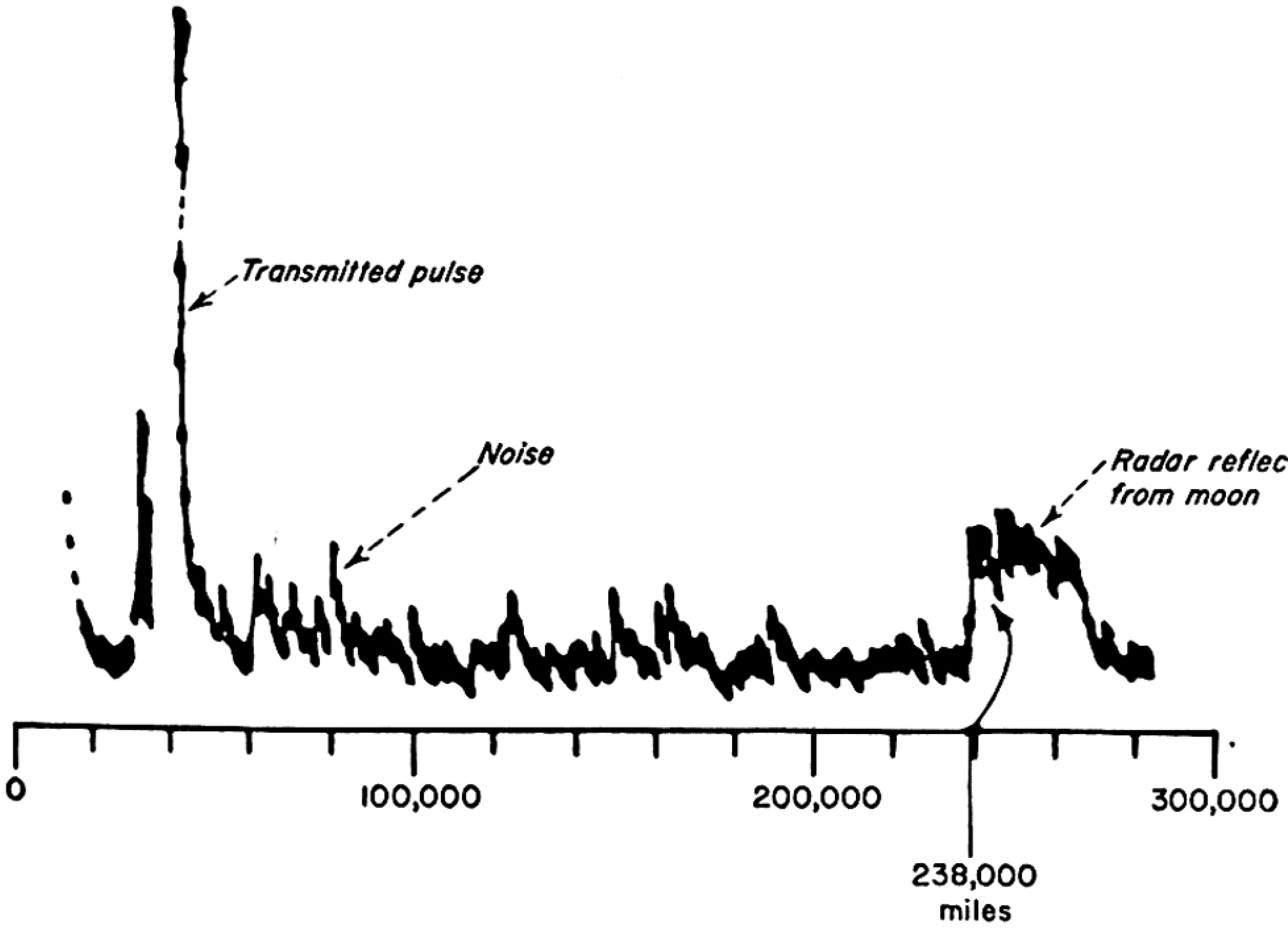

FIG. 7-3. Radar signal from the moon. Time of travel method.

**Radar.** The location of aircraft (and other objects) by electromagnetic pulses of energy is referred to as *radar*. The time of travel method is most commonly used (Fig. 7-3).

The basic radar method is simply indicated in Fig. 7-4. A transmitter produces a suitable short radio-frequency pulse, which may last for about 1 μsec or less. These pulses are made to occur periodically, but with a quiescent interval between them that is much greater than their own length. They are then propagated from a highly directional antenna. After they are transmitted, the transmitter is switched off and the receiver is activated.

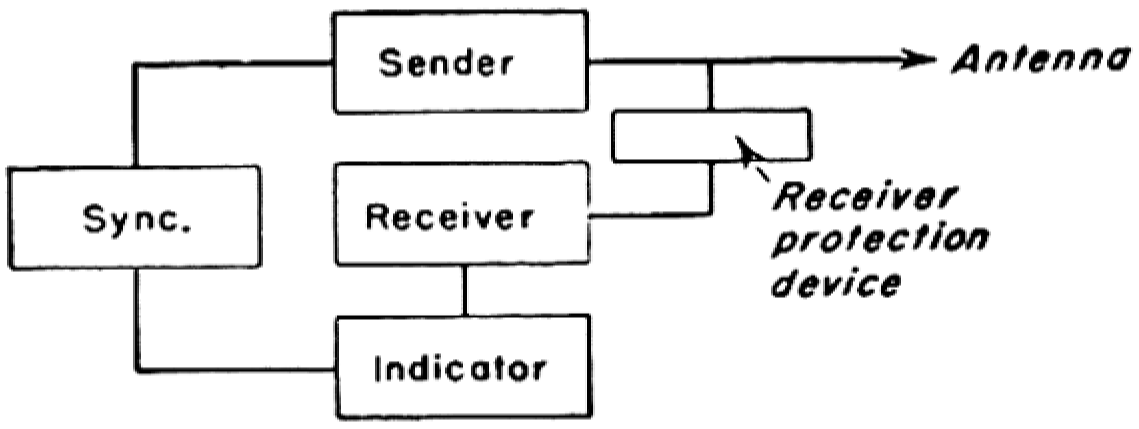

FIG. 7-4. Radar system.

Radio-frequency energy returning after reflection from a target is picked up and amplified by the receiver. These signals may be either detected or not. In any case they are impressed on an indicator, which is usually a cathode-ray tube. The form of indication may be one of several. For illustrative purposes, it may be considered as a sweep with the pulse and, after an interval, the reflections indicated on it. This is commonly called an *A scan*. If the sweep is linear, or if suitable time marks appear on it, such as pips, the distance between transmission and reception can be easily read. Naturally the whole unit must be suitably synchronized so that jitter does not exist.

In radar it is preferable to use a single antenna for both sender and receiver. This is also true in much ultrasonic work. However, when this is done, the receiver must be suitably protected to prevent blocking due to the very high amplitude pulse. A switching arrangement known as a TR box is generally used for this purpose.

Because of the short time interval, the radar system may also find difficulty in locating objects very near the antenna. However, while this time was formerly of the order of 0.1 sec in submarine signaling, in radar it is of the order of a fraction of a microsecond.

The radar system uses many types of scan; *i.e.*, the intelligence is presented on the face of a tube in various manners—as a line with superimposed pips, as a map of the area, etc. To date, the A scan is used practically exclusively in ultrasonics. Such a pattern is shown in Fig. 7-5. The pulse appears at the left of the sweep, and markers on the sweep indicate time intervals. The time between the pulse and a reflection can therefore be directly read.

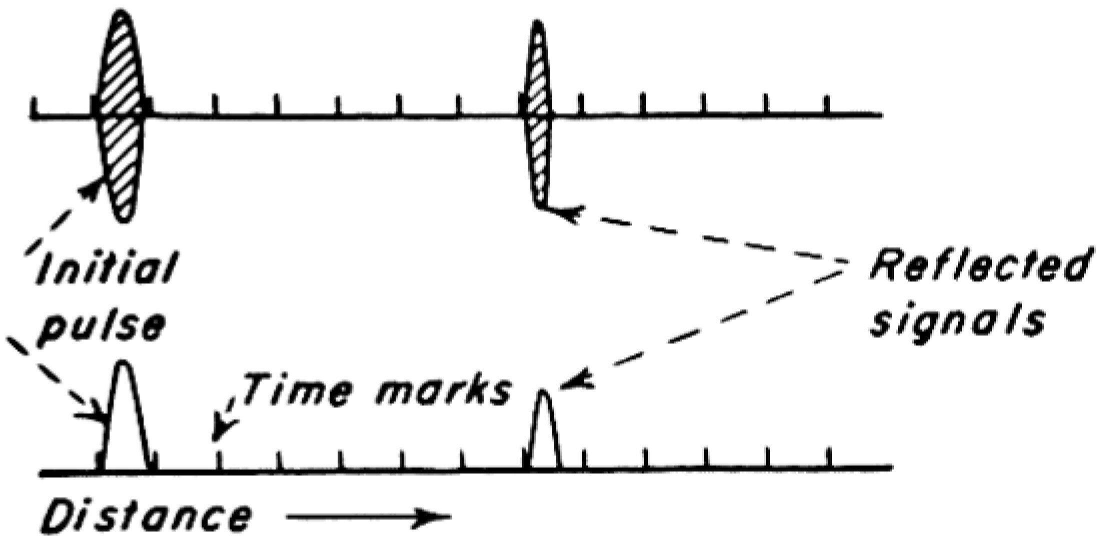

FIG. 7-5. A scan.

The top indication is from a radio-frequency signal impressed on the sweep, while the lower one is detected. Either method can be used. Detected signals are a little more brilliant and allow for greater amplification at a lower frequency. Radio-frequency signals are simpler to obtain and do not displace the base line.

**Seismic Signaling.** A highly specialized type of ultrasonic work is connected with the exploration of the earth by means of transmitted waves. This method is widely used to locate oil wells or mineral deposits. Most of the problems are those intrinsic to generalized pulsed systems except that the time intervals are fairly long.

The operation of the method is roughly as follows: A pulse of sonic energy is provided by a piece of explosive such as dynamite. This is displaced a considerable distance from the receiver and fired to provide a pulse. This pulse takes the form of a train of damped waves, which travels through the earth, is reflected or refracted by various changes in its composition, and is finally received. The receiver activates a mechanism that keeps a continuous record of the different pulses as they are picked up.

The same general principle applies to the seismograph, which is used to record earthquakes, except that in that case only the receiving part of the apparatus is needed, the ultrasonic or sonic energy being provided by shocks in the earth itself.

A typical geophysical system is shown in Fig. 7-6. The chart at the top represents the arrival of successive waves from various layers at different depths, each of which is received at a time interval depending upon its time of travel. In this manner reflections from different strata in the earth are individualized. The first signal to be received will naturally be the direct wave, *i.e.*, that portion of the energy which travels in a straight line between sender and receiver.

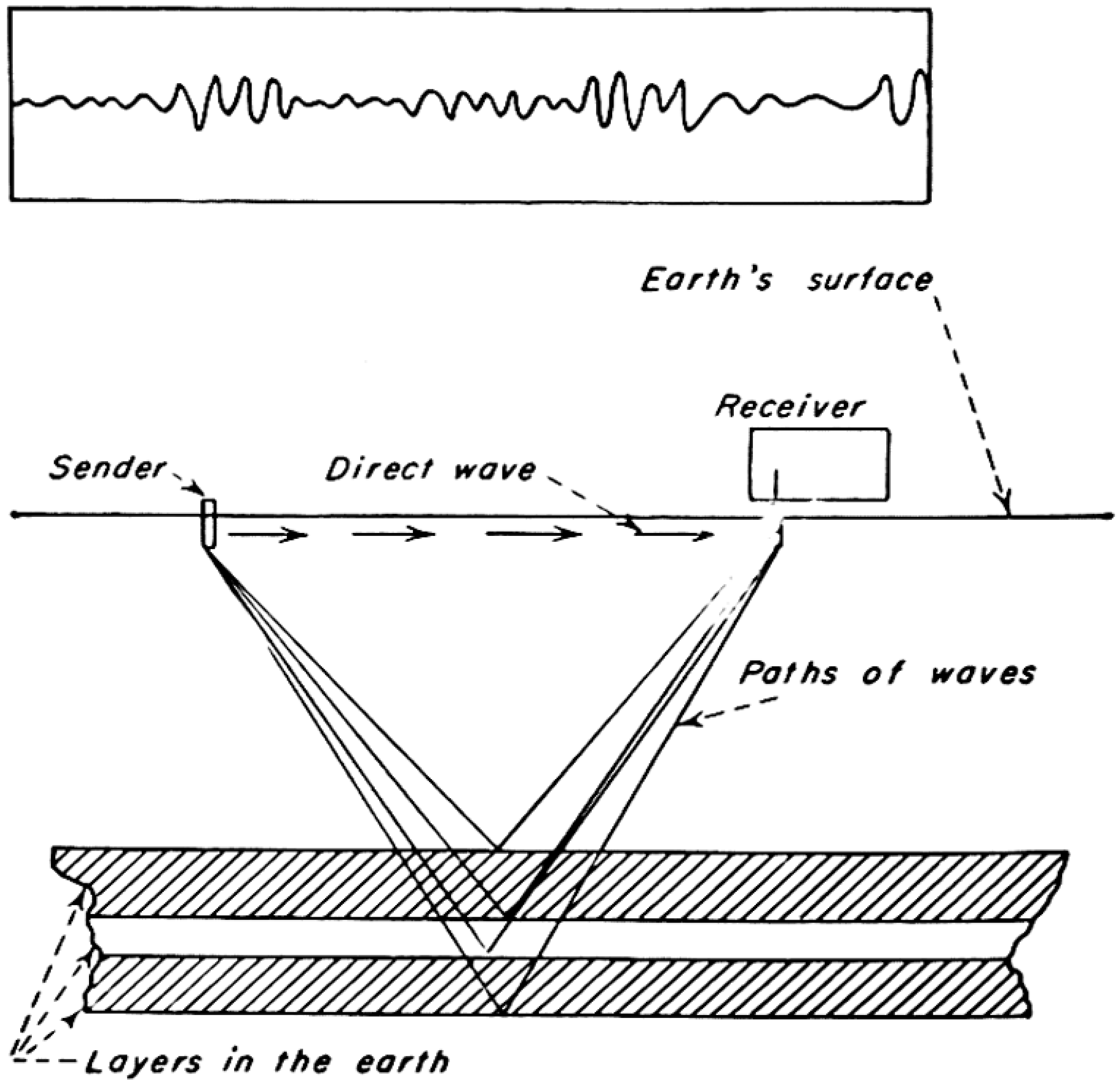

FIG. 7-6. Seismic system.

Highly sensitive methods are used for seismic listening, and ultrasonic waves in the earth (caused either by earthquakes or from artificial generation) obey all the laws of general ultrasonic propagation.

**Sonar.** The submarine signaling systems already mentioned are sometimes referred to as *sonar* (sound navigation and ranging). These methods are similar to the radar ones except that the form of the transmitted energy is ultrasonic.

The frequencies are of the order of 10,000 to 40,000 cycles, and mechanical, visual, or aural means of indication may be used. The sending transducer is usually a magnetostriction unit because of its ruggedness and high power-handling abilities. Both magnetostriction and crystal transducers are used for listening. Generally the crystal type is used where greater selectivity is needed. In some cases there is no means of transmitting a pulse, but listening means are provided by which sounds such as those made by a ship's motors or propellers can be picked up.

In most systems the method is the same: A pulse of ultrasonic energy is transmitted, the reflections from a target received, and the time interval indicated. This gives the distance between the unit and the target. Sharply directional units may be used to range as well, *i.e.*, determine the angle or direction at which the target is traveling. These units are so highly developed that often many characteristics of the target can be deduced, such as speed or size.

Placement of a sonar installation on a submarine is shown in Fig. 7-7.[1] A description of a typical sonar installation may be of some value. The block diagram of such a system is shown in Fig. 7-8.

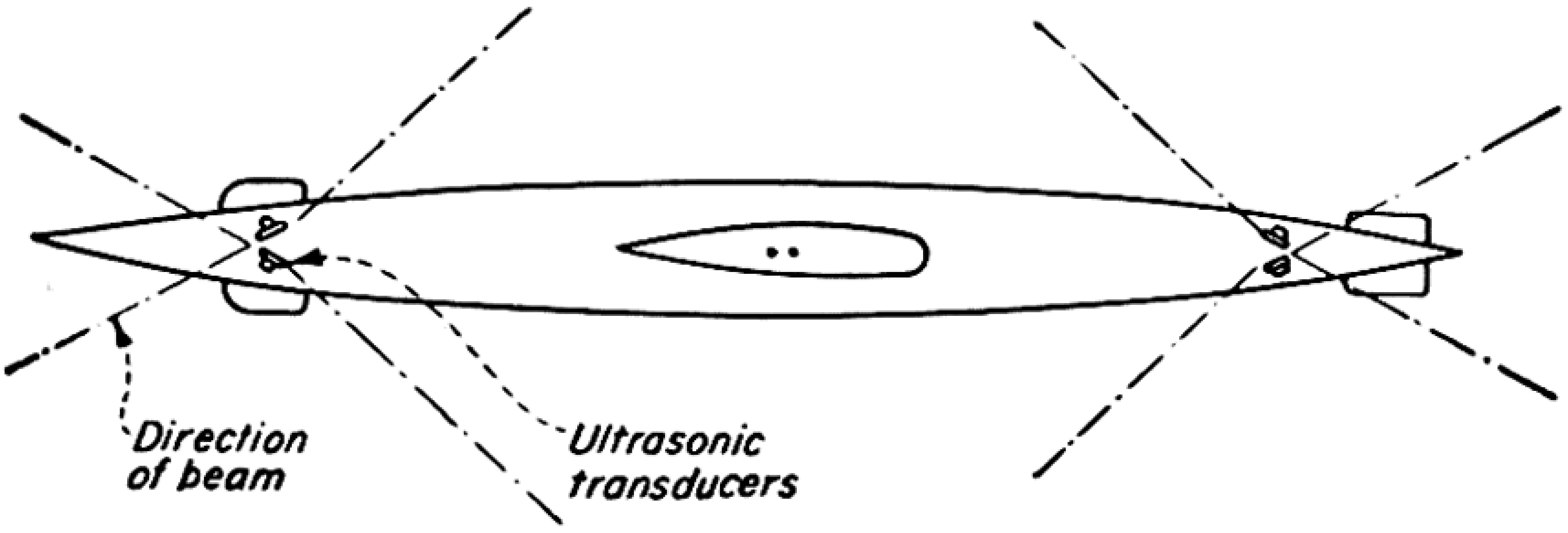

FIG. 7-7. Sonar installation.

The oscillator provides a pulse of ultrasonic waves at about 25 kc and with a power output of approximately 600 watts. This energy is sent out in pulses about 0.1 sec long, with a quiescent interval of several seconds' duration between two successive pulses. Pulsing may be carried out by a relay for time durations of this order.

A magnetostriction unit is located in a housing projected down under the water level. This unit is arranged so as to be connected to the pulse generator during transmission and (if it is used as a receiver also) to the receiver during the reception of echoes. The unit is ordinarily highly directional and can be rotated to get azimuth readings.

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[1] W. Hahnemann, U.S. Patent 2,017,695, Oct. 15, 1935.

The amplifier may be of the superheterodyne type. Indicators may be aural (loud-speaker or phones) or visual (range scope).

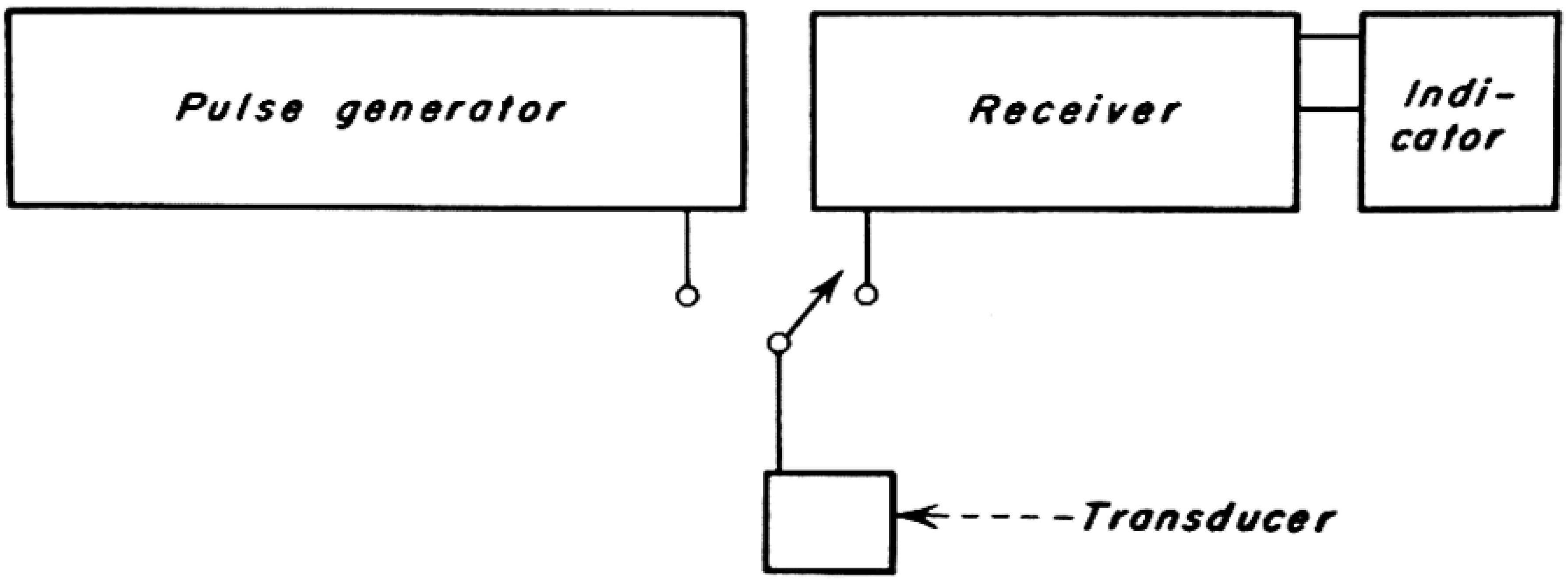

FIG. 7-8. Sonar system.

Some units measure the time between pulse and echo by triggering the next pulse with an echo (which actuates a relay in the receiver output).

One of the first and most successful range indicators was a neon bulb positioned behind a disk with holes in it, with the holes calibrated for range. The bulb rotates on a wheel at a fixed rate.

When the neon bulb is behind the hole that corresponds to zero, a mechanical arrangement fires the initial pulse. The bulb then travels around until an echo is received, when it flashes. The flash is seen through one of the calibrating holes, and the distance can be read from it. The bulb will repeat its flash in the same position on each rotation, providing a stationary mark. Several variations of this arrangement are still widely and successfully used.

The design of the various sections of sonar systems may be found in the literature and is fairly straightforward. However, certain considerations are of importance.

In underwater signaling, spurious signals, *i.e.*, reflections within the medium, etc., may cause difficulty in separating and interpreting the working signal. The problems are similar to those found in continuous-wave systems. One method of avoiding this, used successfully in submarine work, is to sweep the pulse frequency over a narrow range, *i.e.*, about 1,500 cycles. This prevents the build-up of standing waves. The theory is explained in the section on resonance.

When superheterodyne amplifiers are used in sonar, they are usually inverted; *i.e.*, the local oscillator operates so that the intermediate frequency is above the signal frequency. This must be done because the signals are of such low frequency. Various methods are used to gate the receiver's sensitivity while the pulse is being sent out. The output may or may not be detected. Such receivers may also have a variable band pass.

Sonar systems are naturally more complex than indicated here. However, the material under electronic consideration also applies very largely to them.

**Testing Materials with Pulsed Ultrasonics.** The original work in the use of pulsed ultrasonic energy for the testing of materials was disclosed in U.S. Patent 2,280,226, issued in April, 1942, to F. A. Firestone. This invention solved many of the problems that had been plaguing users of ultrasonics and gave great impetus to ultrasonic research, leading to many later inventions and refinements. The method is simple, quick, and positive and has essentially eliminated most of the difficulties inherent in all systems developed prior to that time.

Dr. Firestone calls his instrument the Reflectoscope. It locates defects by means of the echo principle, which had been extensively used in both sonar and radar, to which ultrasonic testing by the pulse method bears striking and basic similarities.

As in these other fields, the basic principle of operation consists of the transmission of a pulse of vibration into the part or medium to be inspected and the measurement of the time intervals between the initial pulse and the arrival of the reflections from internal defects and from the opposite side.

When the medium is metal and a few inches wide, the reflections return a few microseconds after the pulse is emitted, and the Reflectoscope accordingly provides a method of measuring these small time intervals.

Such a method offers great possibilities in testing objects where only one face is available or which are many feet long, where the defects lie totally within the part and may not be found by any other means. Moreover, the method is totally nondestructive and can also be used to determine physical properties of the material, such as the amount of absorption or velocity of ultrasonics.

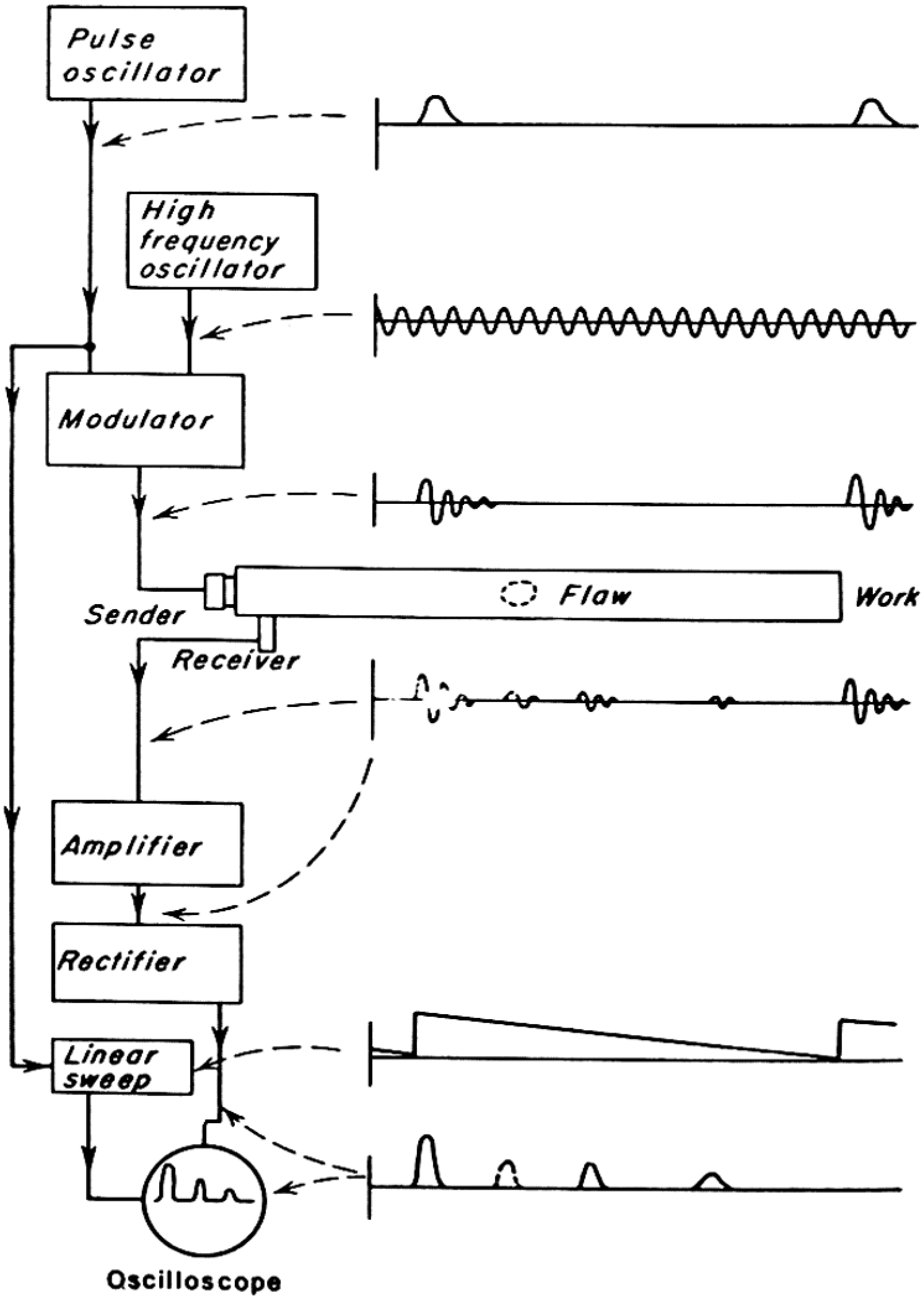

FIG. 7-9. The Reflectoscope.

In most cases 30 ft of material can be easily penetrated and therefore tested with one application of the testing transducer.

A major advantage of ultrasonic testing is that the thickness of the medium does not dictate the size of the flaw that can be located, as, for example, it does in X ray, and a very small defect is practically as easily found in a part 6 ft thick as in one 6 in. thick.

The exact operation of the Reflectoscope and of other devices of the same type is disclosed in the patent (Fig. 7-9),[1] which includes the elements of the operation, as well as the wave shapes associated with each.

The pulse generator produces a radio-frequency pulse a few microseconds in duration and between a few hundred and several thousand volts in amplitude. Raising the voltage does not necessarily raise the sensitivity proportionately, and 500 volts will work very well. This oscillation is then impressed on a crystal, which is placed up against the article under test, with the usual thin film of couplant between.

The receiving crystal may be the same one that sends out the energy, used during the time it is quiescent, or a separate one placed anywhere on the work. The time elapsed between the pulse and reflection is indicated on the cathode-ray tube. When the crystal is off the work, only the initial pulse shows, giving a starting indication from which the time is to be measured. After contact is made with the work, subsequent reflections are received by the amplifier, and each reflection is indicated at a particular time after the initial pulse, which represents the distance that some part of the energy has traveled.

Thus, if an oscilloscope is used for the indicator, which is the most convenient method to date, the initial pulse would occur to the left of the line and the echoes spaced after it to its right.

The reflected energy will bounce back and forth in the medium, indicating over and over again until it is damped or attenuated by the physical properties of the medium and also by losses in other parts of the system. The instrument should be so designed that the reflections from one pulse entirely die out before the next one is sent out; otherwise reflections from the successive pulses will overlap each other, and it will be impossible to tell which is which. The time between pulses is accordingly made long enough so that this does not occur. A 60-cycle repetition rate has proved satisfactory.

A typical picture of a pulse and its successive reflections is shown in Fig. 7-10. It will be noted that the energy is reflected within the material many times.

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[1] F. A. Firestone, U.S. Patent 2,280,226, April 21, 1942.

The action of the ultrasonic energy can be visualized from Fig. 7-11.[1] The pulse is impressed on a block of material and also appears on a sweep at the same time. It then begins to travel through the material until it hits a discontinuity, where part of the energy is reflected and the remainder continues to travel through the article under test. The reflection is thus picked up by the crystal, which now acts as a receiver, and is impressed on the sweep as a pip. Then, after a further interval of time, the reflection from the back face returns and indicates on the screen. The whole process repeats over and over, providing a stationary pattern that can be easily read by the operator.

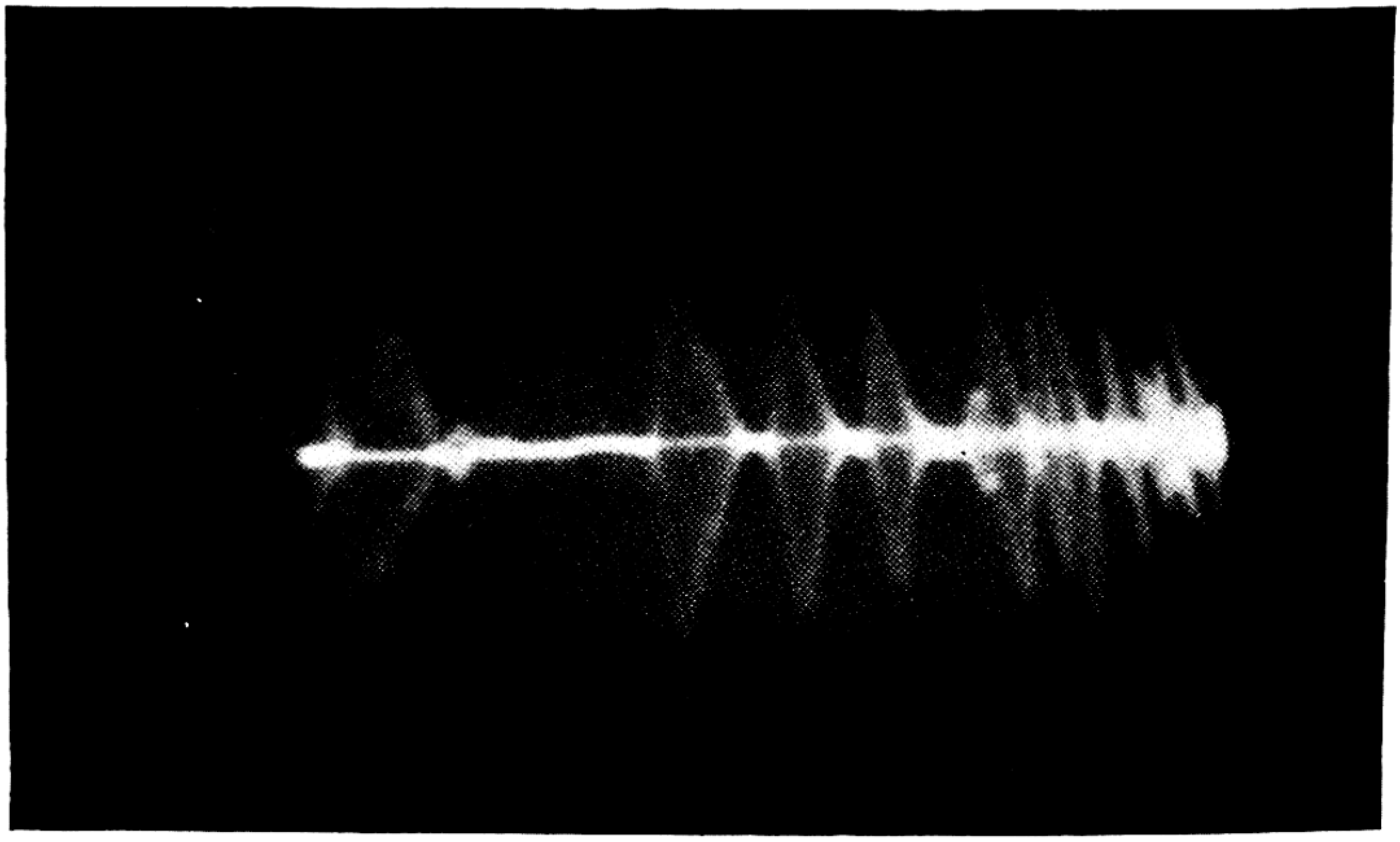

FIG. 7-10. Typical signal result.

**Hughes Ultrasonic Instrument.** Henry Hughes and Sons, in England, have produced an instrument[2] operating on the reflection principle but differing considerably from the Firestone one in certain respects.

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[1] B. Carlin, Supersonic Examination of Materials, *Product Eng.*, October, 1947.

[2] C. H. Desch *et al.*, The Detection of Cracks in Steel by Means of Supersonic Waves, *J. Am. Welding Soc.*, Supplement, January, 1947.

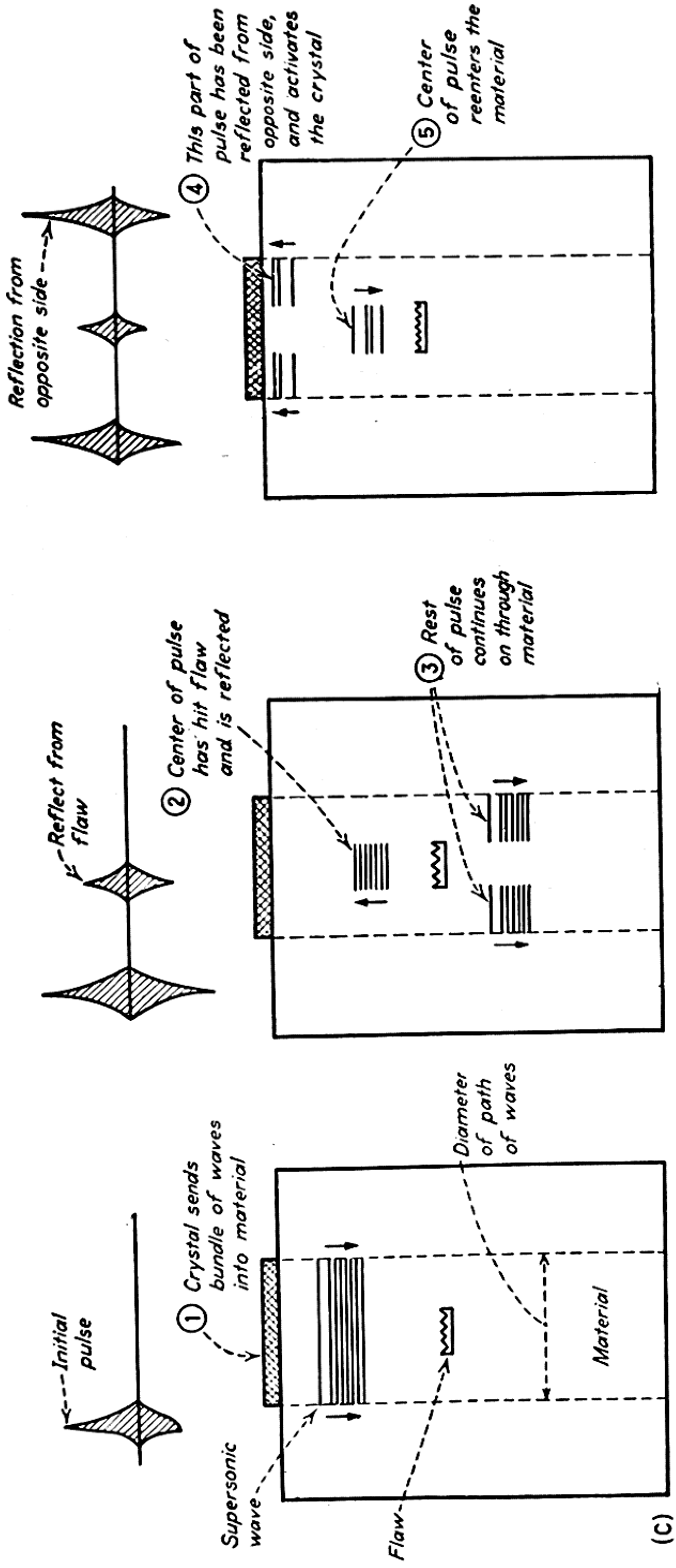
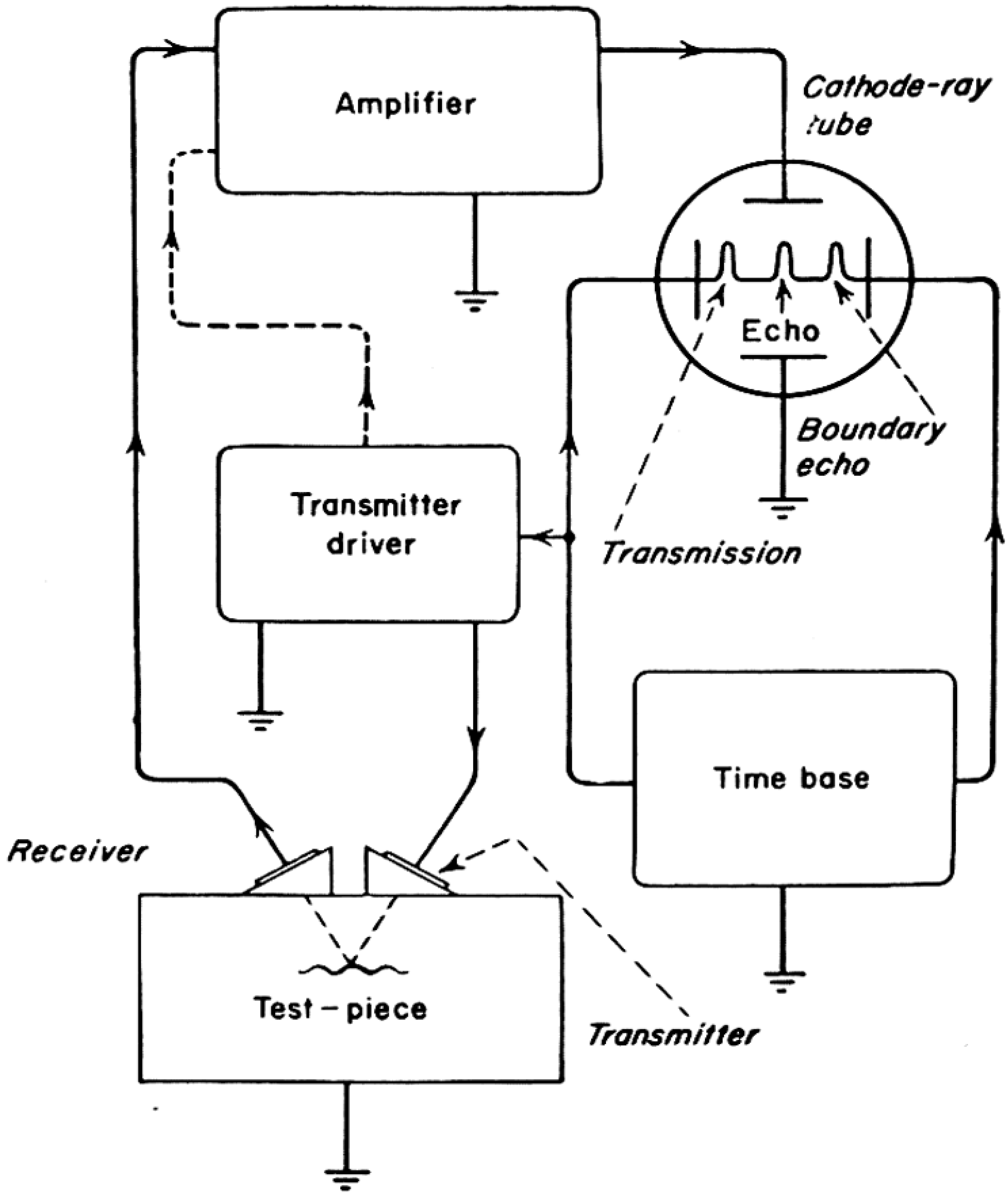

Initial pulse
① Crystal sends bundle of waves into material
Supersonic wave
Flaw
Diameter of path of waves
Material
(C)
Reflect from flaw
② Center of pulse has hit flaw and is reflected
③ Rest of pulse continues on through material
Reflection from opposite side
④ This part of pulse has been reflected from opposite side, and activates the crystal
⑤ Center of pulse reenters the material

FIG. 7-11. Action of ultrasonic pulse.

Figure 7-12 shows the operation of the instrument. Certain basic similarities may be noted. In the unit a triggering circuit supplies firing signals to the sweep and after a short delay to the pulse generator. The pulse generator is a gas tube, the British equivalent of the 884. A pulse of energy, *i.e.*, of logarithmically damped ultrasonic waves, is then sent out by the transmitting crystal, shown mounted on a wedge.



(*a*)

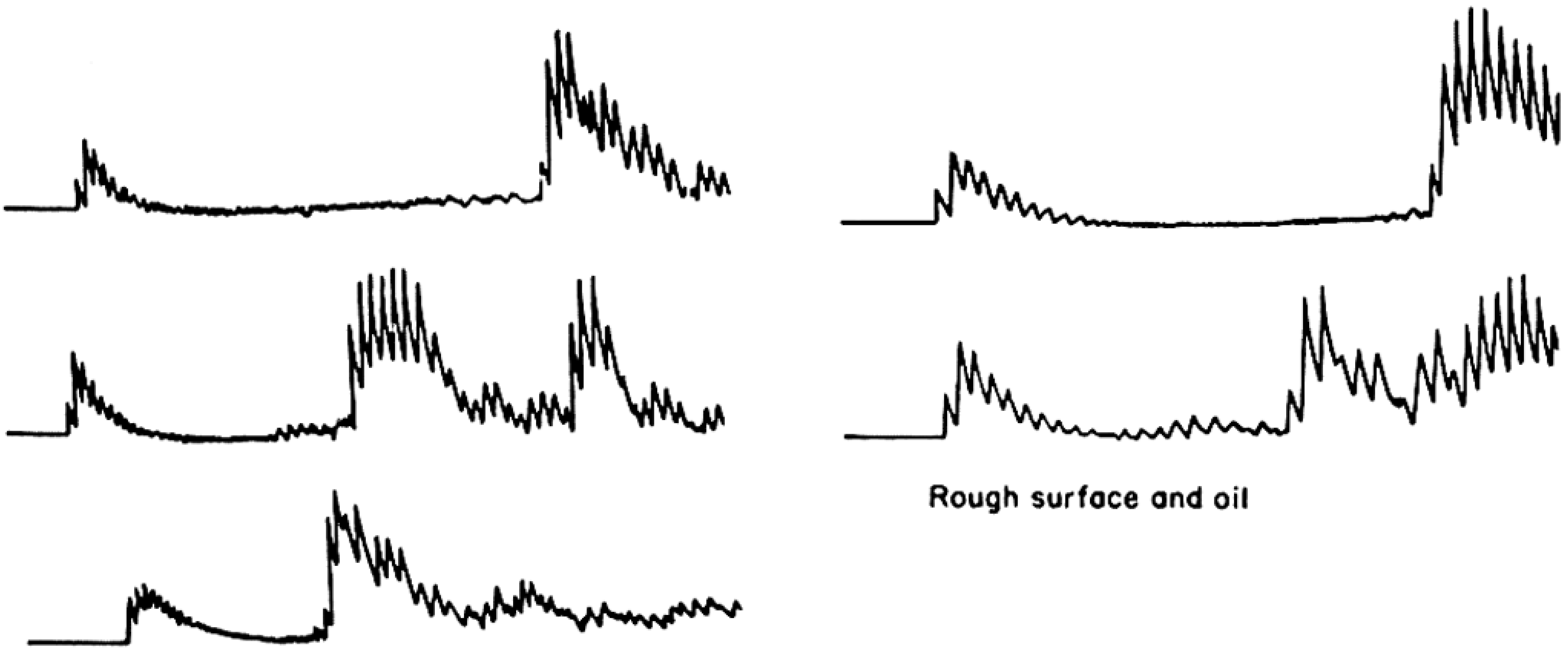
FIG. 7-12. British instrument: (*a*) block diagram, (*b*) typical signals.

This wedge directs the beam of ultrasonic energy into the part under test, and the receiving crystal is also tilted so that it is sensitive only to the energy from the particular region under test. There is no refraction due to the wedge, which is of the same material as the medium. This wedge method of test suffers from certain basic difficulties of application. It is hard to handle, and the wedges must be continually readjusted if an area is to be tested. However, flat crystals can also be used, but the instrument can operate to date only with two separate crystals, which makes it cumbersome. The received signal is amplified and appears as a vertical detected pip on the screen of a cathode-ray tube.

The crystals used are about 0.75 in. in diameter and operate at a resonant frequency of 2½ mc. They are therefore about 0.1 cm thick. The transmitter pulse generator generates a pulse of approximately 300 volts amplitude on the sending crystal. This pulse is produced, as indicated, by discharging a condenser through a thyratron.

The amplifier is a video type, inductance compensated, with a response flat up to 2½ mc and then gradually falling off up to 5 mc. The triggering circuit is a generator of square waves, which is followed by means of differentiating them to produce the short sharp pip used in the triggering action.

There are no markers, except a rulerlike etching on a screen placed over the tube. The sweep must therefore be linear and is produced by a thyratron being fired in the usual manner through a pentode, which gives greater linearity. Blanking voltage is applied to the cathode-ray tube to obliterate the return trace.



Machined surface and oil

Rough surface and oil

(*b*)

The Hughes company claims to be able to find flaws between ½ in. and 12 ft from the testing surface in steel.

Figure 7-12 shows a typical indication on a Hughes-type instrument. One interesting feature of this instrument is the fact that only one crystal is used for all frequencies. The instrument operates at $\frac{5}{8}$, $1\frac{1}{4}$, $2\frac{1}{4}$, and $2\frac{1}{2}$ mc to date, but a $2\frac{1}{2}$-mc crystal is used throughout and is driven at the other frequencies. This makes the handling of crystals and cables simpler and easier.

**Pulsed Systems.** *Electronic Considerations.* The late war contributed greatly to the development of electronic measurement techniques and particularly to those which were related to pulse production and measurement. Such developments have had wide influence on all forms of equipment; and since ultrasonics has come to depend almost exclusively on electronic equipment for the production of energy and also for its measurement, it also has felt the results of this work.

Although, strictly speaking, the electronic considerations are not a part of ultrasonic knowledge, the fields are now so connected that no treatment of ultrasonics is complete without consideration of the associated devices. Therefore, a brief discursive description of the typical circuits used in pulsed ultrasonic equipment may be of considerable value in defining some critical aspects of the problem.

This treatment will indicate the types of circuits used. Block diagrams will be used whenever possible, since once the type of circuit is known, design considerations can be found in any engineering text. However, those electronic problems which are characteristic of ultrasonics will be considered in greater detail.

**The Pulsed Ultrasonic Tester.** The type of systems and circuits discussed hereafter is particularly adapted to test and signaling purposes. However, by minor changes in circuit constants, the apparatus can be adapted to other types of ultrasonic application. The principles apply equally well to all phases of the work.

The fundamentals of the pulsed ultrasonic system may be seen in Fig. 7-13. In its most general form, the system is similar to a pulsed radar unit, and such devices can sometimes be adapted for ultrasonic work. However, ultrasonic apparatus is of lower frequency and power.

The ultrasonic system should produce a pulse ranging in length from 1 to 10 $\mu$sec. This length may be adjustable. It should operate over a frequency range of 100,000 cycles to about 10 mc and have a peak-to-peak pulse voltage of 300 to 1,500 volts. The amplifier may be either tuned or untuned, with a gain of about 10,000 or greater.

The system consists of a pulse generator, which produces the pulses mentioned and impresses them on the crystal. This initial pulse provides the marker from which all time is measured; and in those cases where two crystals are used and the coupling between transmitter and receiver is insufficient for this indication to be picked up and appear on the screen, part of the signal may be taken and used for this purpose.

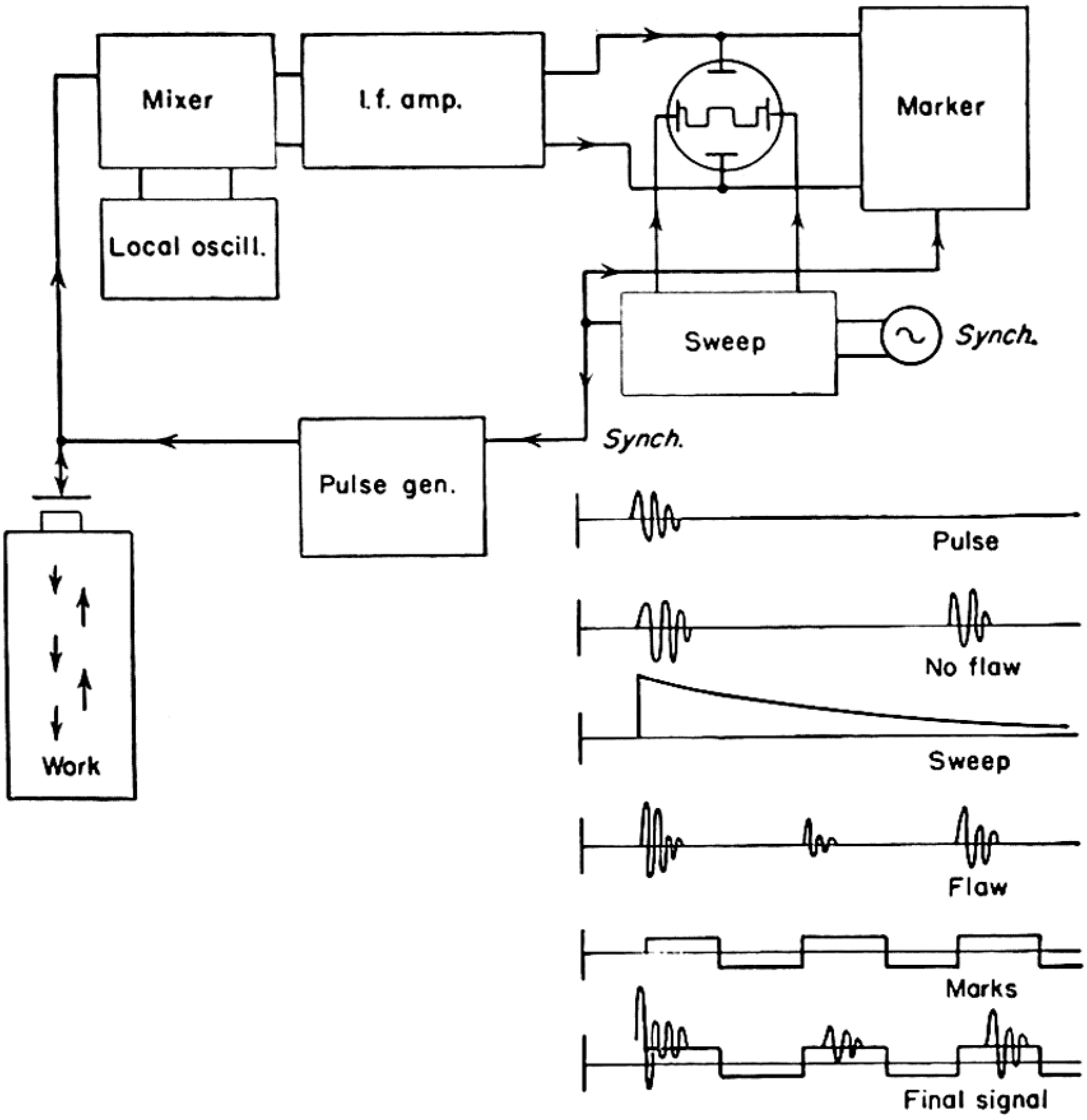


**FIG. 7-13.** Pulsed ultrasonic tester.

The pulse is synchronized to the sweep generator in those cases where a cathode-ray tube is used as indicator. In the discussion here, that method of indication is considered exclusively, since it is at present the simplest and most economical. However, there is no electrical or ultrasonic reason why other types of indication should not be used. The pulse and sweep must be synchronized so that there will be no mutual jitter between them, which makes the signals fuzzy and hard to read.

The synchronization, or sync, signal is usually taken from the sweep circuit. If it is desirable to delay the pulse after the start of the sweep, the signal from the sweep can be used to actuate a suitable delay circuit, which may be fixed or variable, and the delay circuit will produce another signal, after a suitable time delay, which performs the function of triggering the pulse.

The transducer is coupled into both the transmitter and receiver. Either two separate transducers or a single one may be used. The amplifier acts upon the received signal, which is then impressed on the indicator and appears as a series of pulses or pips after the initial pulse. The band width of the amplifier must be sufficiently great to produce separation of the signals without great loss of gain.

The time is then read between the initial and reflected signals. To do this, either a calibrated linear sweep must be used or suitable marks for timing purposes impressed on the sweep.

**Sweep.** Any of the ordinary circuits used for generating a sweep can be used on the cathode-ray tube. The duration of the sweep should be so chosen that it is sufficient for the longest possible range which would result from sending the ultrasonic energy through a very large mass of material. At the same time it must be sufficiently fast so that variations occurring close to the initial pulse can be observed. For this reason, sweep circuits used in ultrasonics are usually variable by either switched or continuous means.

A sweep allowing enough time for about 30 ft of steel or aluminum would be very difficult to use in a few inches of the same material or in other materials except those where the speed of transmission is much slower, as it is in plastics and some liquids. Since ultrasonic waves travel about 1 ft every 100 $\mu$sec, a 30-ft sweep would be one of about 3,000 $\mu$sec. The shortest range for ordinary work is usually about 2 in., which corresponds to 16 $\mu$sec in aluminum. Thus a sweep to be completely satisfactory should be variable over a range from 16 to 3,000 $\mu$sec for testing materials.

Sweeps for other purposes can be computed in the same manner after the minimum and maximum range has been determined.

Circuits may be of either the hard or gas-tube type and of any of the conventional kinds. The start of the sweep would normally be on the charge side; otherwise the action will commence with a flyback, and a corresponding delay must be introduced to get the pulse to occur on the usable sweep. The sweep need not be particularly linear, since in most cases where exact distances are to be measured, marker circuits will be included.

**Sweep Operation.** The simple sweep circuit (Fig. 7-14) illustrates the operation of all gas-tube sweeps. The condenser and resistor values determine the time of the sweep, which can then be varied by switching the condenser when a gross change in frequency is desired or by varying the resistor when a vernier on the large changes is more desirable. The condenser will periodically charge up in the usual exponential manner while the tube is not conducting until it reaches a point at which the voltage on it causes the tube to fire. The voltage will then discharge rapidly through it. If it is desired to have the tube fire before the voltage reaches the breakdown point, a synchronizing signal may be introduced on the grid. The point at which the tube fires is then determined by the grid voltage.

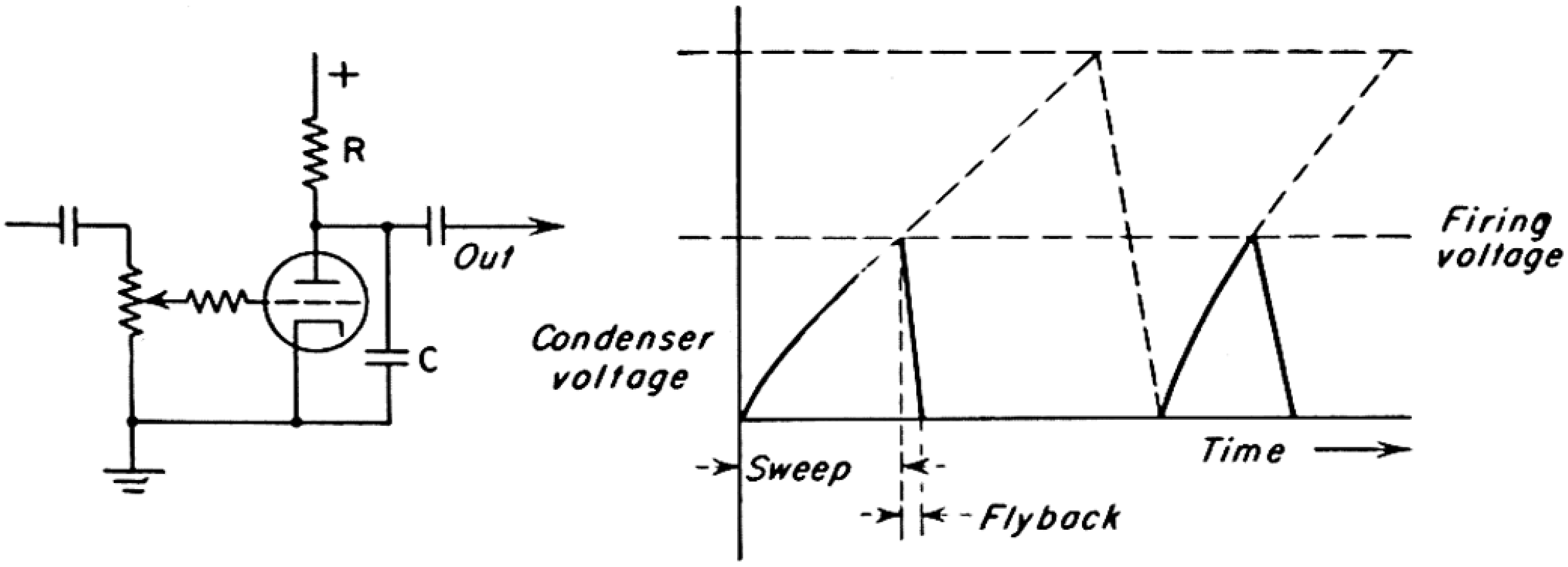


FIG. 7-14. Simple sweep.

When the voltage on the tube drops to a point so low that plate current cannot be maintained, the tube will recover and the condenser again charge.

The flyback time is the time required for the discharge through the tube, and the sweep time is the time that the condenser takes to charge. Flyback time should naturally be kept as low as possible in order to keep the flyback trace from being too bright and interfering with the actual working sweep. In certain cases it is necessary to bias out the flyback voltages by means of a blanking signal on the cathode-ray tube grid or cathode.

A sweep can be constructed so that the flyback occurs before or after the working sweep; *i.e.*, the tube may be normally conducting or nonconducting and thrown into the opposite condition to produce the sweep.

Either a portion of the saw tooth produced or the whole signal can be used on the cathode-ray tube depending on the linearity desired. In ultrasonic applications linearity is not particularly necessary.

As already indicated, if the trigger for the pulse is taken from the sweep, the sweep should start with the charge of the condenser; otherwise the additional delay interposed by the flyback time will cause the pulse to appear on the back trace unless it is suitably delayed.

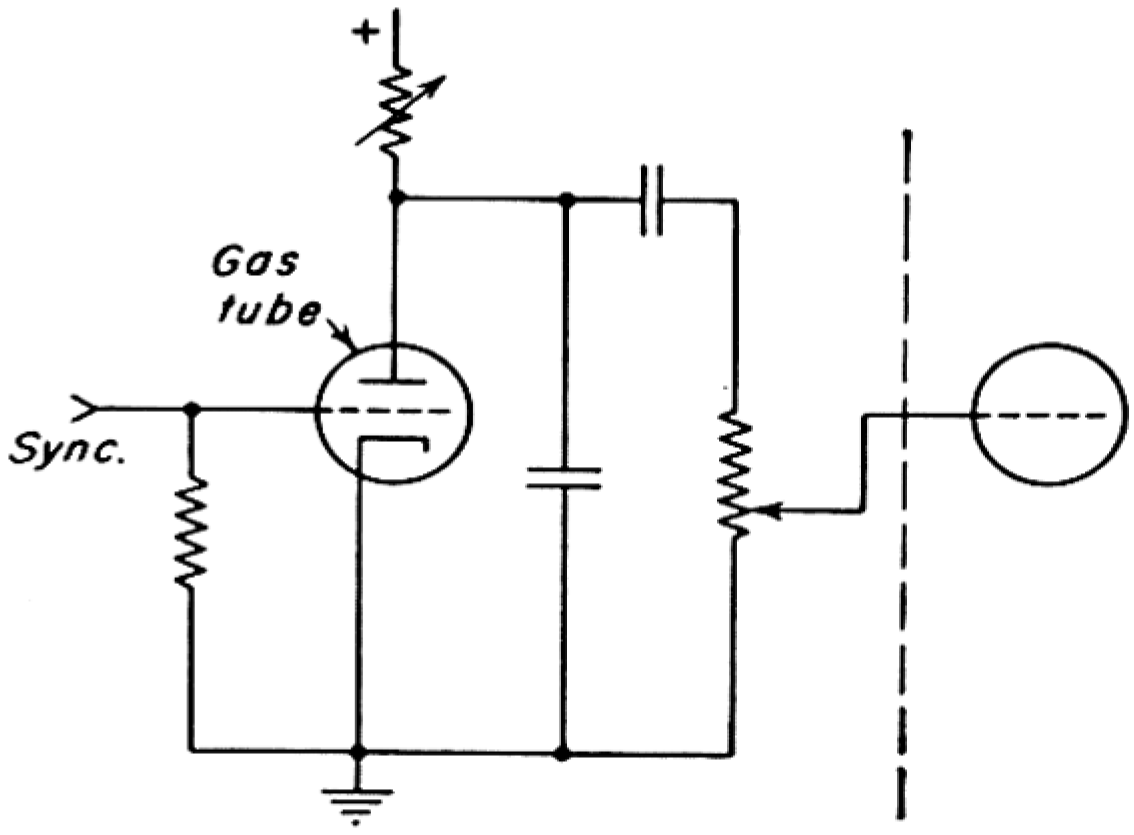


FIG. 7-15. Sweep system.

Such a trace has been satisfactorily used to give time axes of the order necessary. The circuit shown in Fig. 7-15 gives all the essentials of an entire system. The circuit can be adjusted by one or two potentiometers to the full extremes of the times necessary without the necessity of additional switching.

**Delay Circuits.** The term *delay circuit* may be taken to refer to any circuit that can be activated by a suitable signal and that some time later delivers another signal which can be used to control some process. The order of delay usable in ultrasonic work may vary between zero and a few hundred microseconds and usually, though not necessarily, represents the time delay between the start of the sweep and the firing of the pulse. If this delay is variable, it will allow the movement of the pulse together with all succeeding reflections relative to the sweep, so that they can be placed on whatever portion it is most convenient to work with. Delay circuits may be of various types. In some cases delay lines can be used, which, because of their electrical characteristics, cause a delay in the signal.

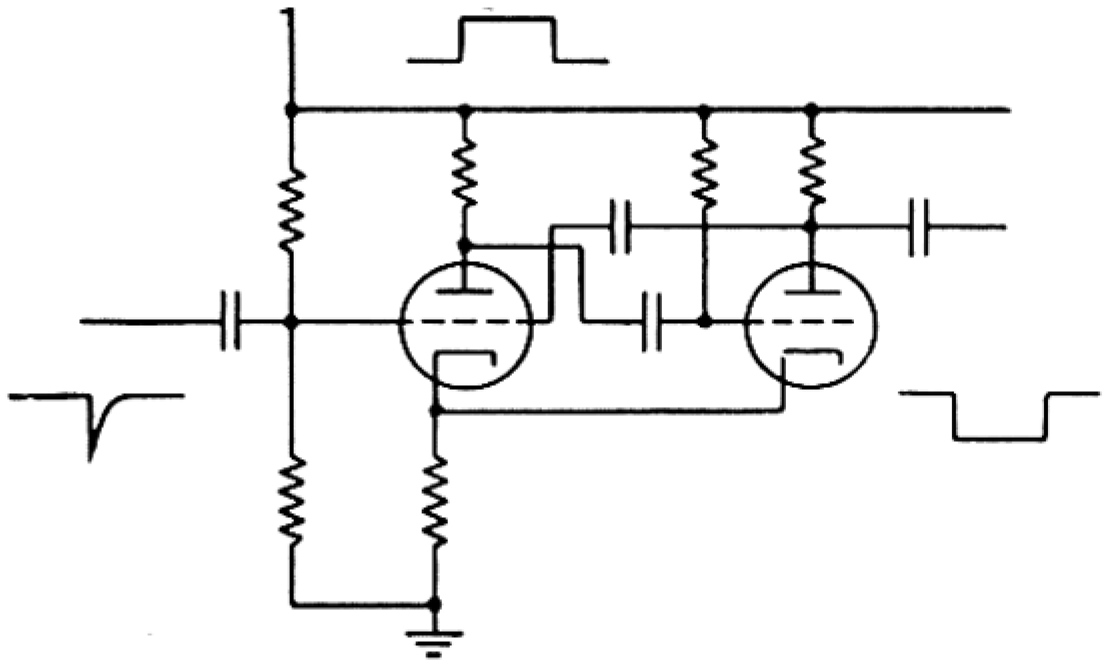


FIG. 7-16. Delay circuit.

A simple variable type is shown in Fig. 7-16. The operation of this type of delay circuit may be visualized in the following manner. The circuit is essentially a single-shot multivibrator. In other words, it has a two-stage resistance-coupled amplifier, in which one of the tubes is cut off while the other is conducting. When a certain point is reached, the tube that has been shut off starts to conduct and the other tube cuts off. The circuit continuously fluctuates back and forth in this manner with the time of conduction determined by the circuit constants. Since the oscillation is extremely sharp, square pulses are produced. Since this tube is biased to be a single-shot type, it will produce one square pulse and then turn itself off.

The time that the tube remains in its unstable condition is determined by the time constant of the circuit elements. Therefore the length of the output pulse, which is a function of oscillation frequency, is also determined by these circuit constants. It can therefore be varied by altering either a condenser or resister. If the square-wave output is now differentiated, the signal that results will be made up of a sharp pip in one direction, either negative or positive, followed after an interval by a sharp pip in the other direction. If the circuit constants are variable, this second pip may be moved with respect to the first one, thus giving a delay between them. If a positive pip is used to fire the delay system and a positive pip derived from it, there is a delay between the start of the sweep, which coincides with the firing signal, and the positive pip, which is produced by the multivibrator. This time delay will be equal to the time duration of the square wave that the multivibrator puts out. Many other systems of time delay have been used, but this one is particularly easy to set up, economical, and foolproof.

**Differentiation.** In order to produce short sharp marks such as pips from a square wave, a circuit referred to as a *differentiator* is usually used. This type of circuit produces a voltage whose amplitude is approximately proportional to the input voltage's rate of change. The circuit consists of a condenser and resistor as shown in Fig. 7-17. The time constant of the combination is extremely short, much shorter than the length of the input signal. The condenser therefore charges in a small part of this length; and since this charge cannot change again, that part of the signal which does not contribute to the condenser charge appears at the output as the differentiated signal. Figure 7-17 also shows the voltage wave shape on the output.

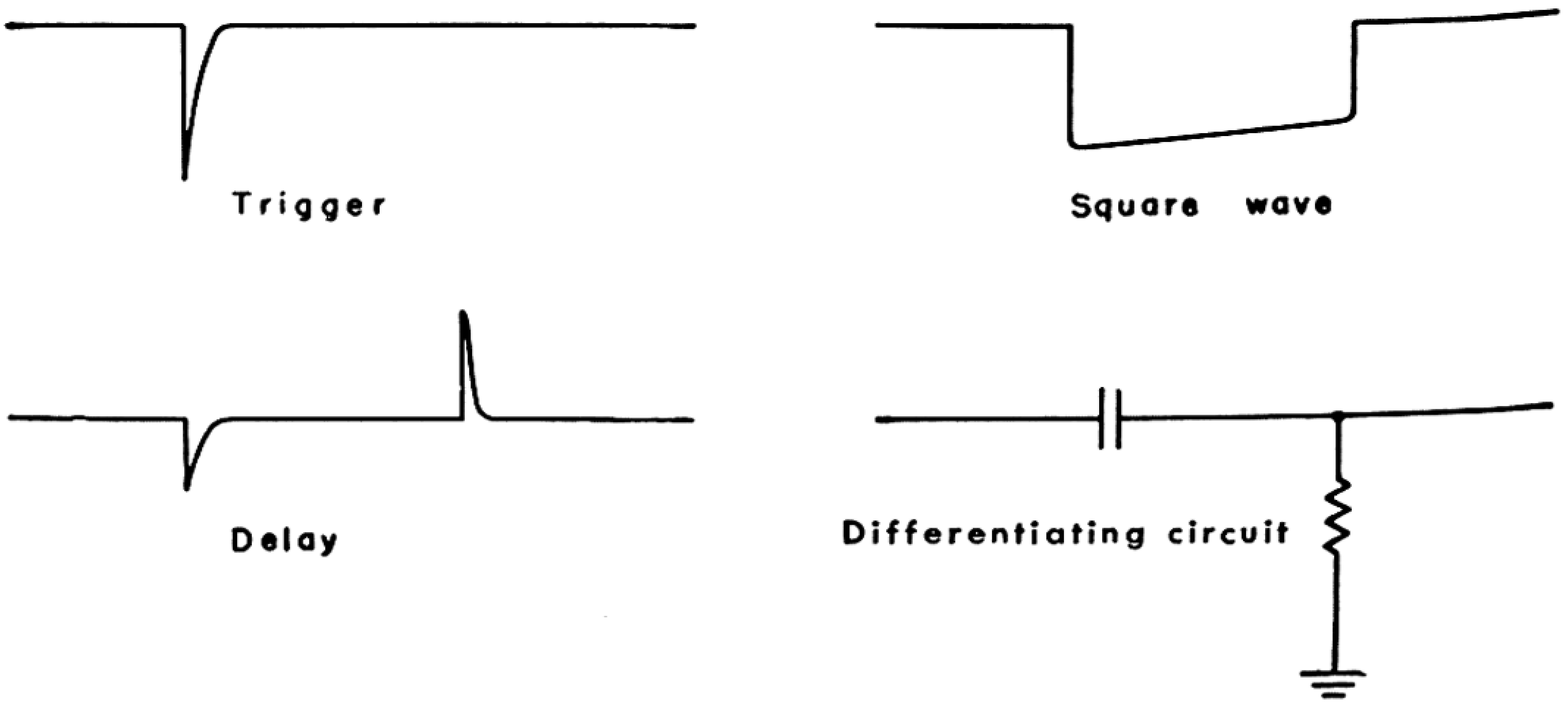


FIG. 7-17. Delay wave shapes.

**Marker Circuits.** The marker circuit is included to provide timing marks, which are impressed on the cathode-ray-tube sweep. These marks are usually introduced on the lower plate, while the signal is impressed on the upper one. However, either plate can be used for either function. The signal and the marks should not both be introduced on the same electrode, since considerable loss in signal strength may ensue owing to the resulting impedance effects.

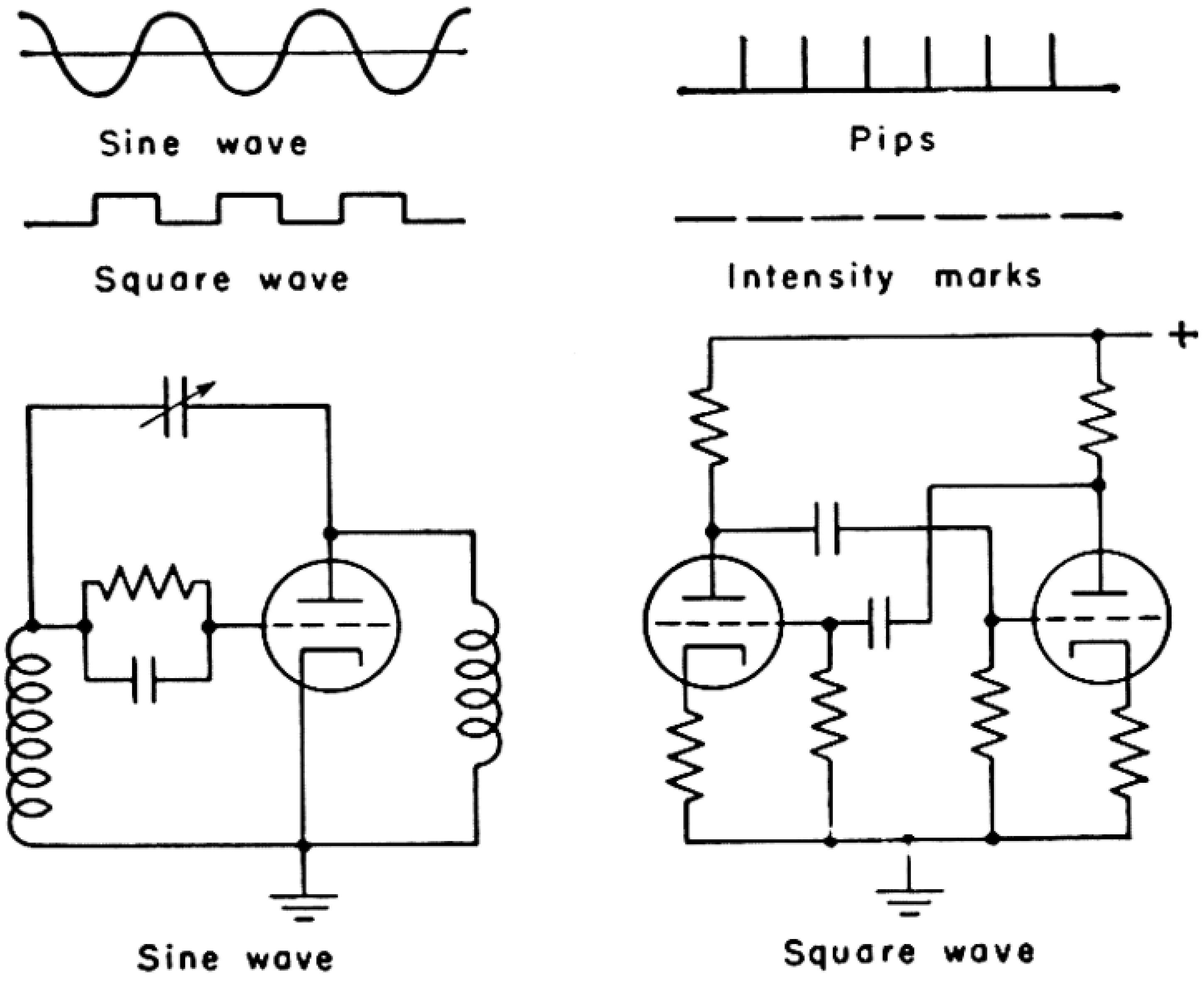


FIG. 7-18. Marker circuits.

Any of a number of well-known marker circuits can be used, and marks may be either of the deflection or intensity type. The first appear as pips; the second show as bright or dark spots. When intensity marks are used, the signal is introduced on the cathode or grid of the cathode-ray tube rather than on its plates.

The marks must be synchronized with the sweep. This is usually accomplished by gating them, *i.e.*, turning them on only for the sweep duration. This may be done by a square pulse, starting with the sweep and lasting as long as the sweep. The two signals are locked together and cannot jitter.

The time of travel in steel is 8 $\mu$sec/in. If time marks are desired, they may be arranged to occur once every 8 $\mu$sec for inches of travel or at suitable intervals for feet or other distances. They may be fixed or variable. One wave every 8 $\mu$sec will be provided by 125,000 cycles of oscillation, and that frequency can therefore be used if inch marks are desired.

The simplest type of marker is the sine wave, which can be provided from an oscillator. Of course, these marks are not very sharp. Square waves or pips are therefore preferred. Pips may all be of the same height or include periodically spaced marks higher than the others to facilitate reading.

The production of square waves by means of a multivibrator or other form of relaxation oscillator is well known. Circuits for this purpose are shown in Fig. 7-18. The waves are usually most nearly square on the tube cathodes. However, they may also be coupled from the plates, and this is sometimes desirable, since the gating signal may appear across the cathode.

These markers can be applied directly to the sweep or shaped into sharper pips by means of a differentiator or other circuit. When the output is too low for direct connection, amplification by one or more stages may be applied. If the marker squareness is not satisfactory, they may be clipped or shaped by auxiliary circuits.

In any case, the oscillator is usually biased off and gated on as described. Various marks are indicated in Fig. 7-18.

**The Cathode-ray Tube.** Power circuits for actuating cathode-ray tubes are well known in the art or can be obtained by request from any manufacturer of such tubes. The voltages provide the necessary electron beam, and the deflections are provided by the amplifier and sweep circuits. Sweep signals are ordinarily impressed on the horizontal plates, and signals on the vertical ones.

**Pulse Forming.** The signal derived from the delay must, in turn, be used to fire or trigger some kind of circuit that will produce a square or nearly square wave of suitable polarity, duration, and magnitude to control the action of the pulse generator.

If there is no delay, this signal is still necessary, but it is supplied directly from the sweep. It takes the form of a semisquare wave of the order of a few hundred volts in amplitude and of a width of 1 to 10 $\mu$sec. The control signal must not be of a greater length than the radio-frequency pulse itself, since its trailing edge will cause spurious signals that appear as pips following the actual power pulse. In those cases where the radio frequency itself is varied in duration, the triggering pulse must be extremely short, in fact shorter than the shortest pulse used. Where the duration of the pulse is varied by the trigger pulse itself, the trigger is always of the same length as the final pulse.

These pulses are usually positive, and one of the simplest methods of producing them is by using a circuit such as Fig. 7-19. In this case a tube is operated with very high plate current normally flowing. When a positive signal hits the grid, it therefore has very little effect. However, when a negative one is used, the tube is momentarily cut off, plate current stops, and the voltage at the plate rises, producing the desired square waves.

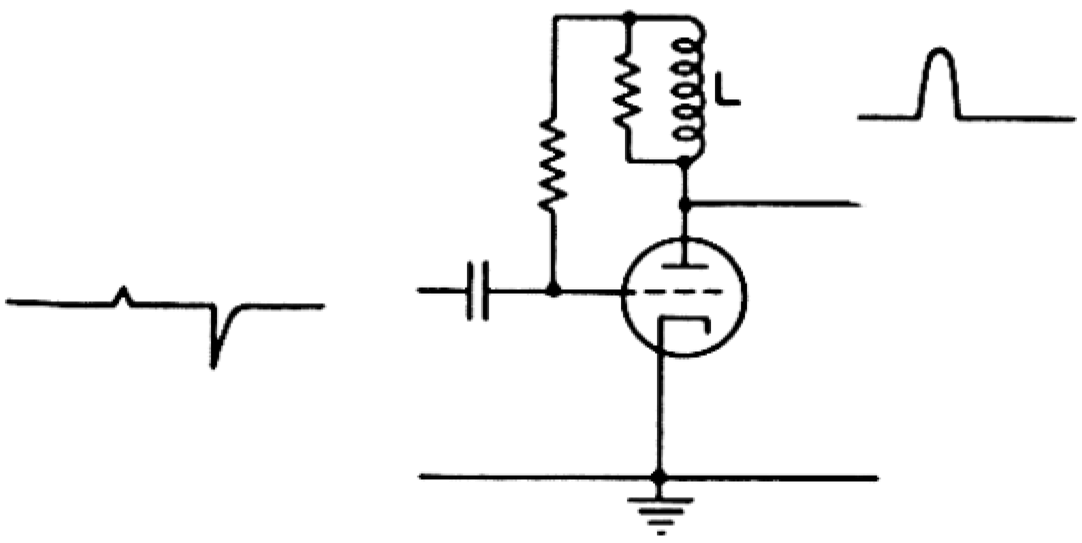


FIG. 7-19. Pulse-forming circuit.

Shock-excited oscillators or blocking oscillators with resonant circuits of low frequency can also be used to produce the pulses when actuated by a suitable triggering signal.

In the case of a shock-excited circuit, the operation is the same as for the overdriven oscillator except that upon being cut off, the resonant coil momentarily rings at its own natural frequency. If this frequency is chosen correctly, it will produce pulses of any specific length. That is, each such pulse is ½ cycle of oscillation, so a ½-mc oscillator would produce a pulse of 1 $\mu$sec length, etc.

Critical damping must be provided by a resistor across the ringing circuit, so that the ringing voltage is damped in only ½ cycle; otherwise the circuit will produce an oscillatory pulse.

In the overdriven amplifier the length of the pulse is a function of the amplifier; in the shock-excited one it may be independent.

There are many more complicated systems, but either of the above is satisfactory.

Whatever the type of pulse-forming circuit, extreme care should be taken to have only one trigger pulse. Any extra or extraneous signals may have the effect of firing the radio-frequency pulse extra times or producing extra oscillations, which appear on the trace and obscure the actual signal.

**Pulse Generation.** Ultrasonic pulse generators are similar to those used in other forms of radiation. A complete circuit, as shown in Fig. 7-20, may consist of a delay, differentiator, amplifier, and pulse generator. It may also consist of a simple pulse generator without delay. In fact, there may not necessarily be synchronization.

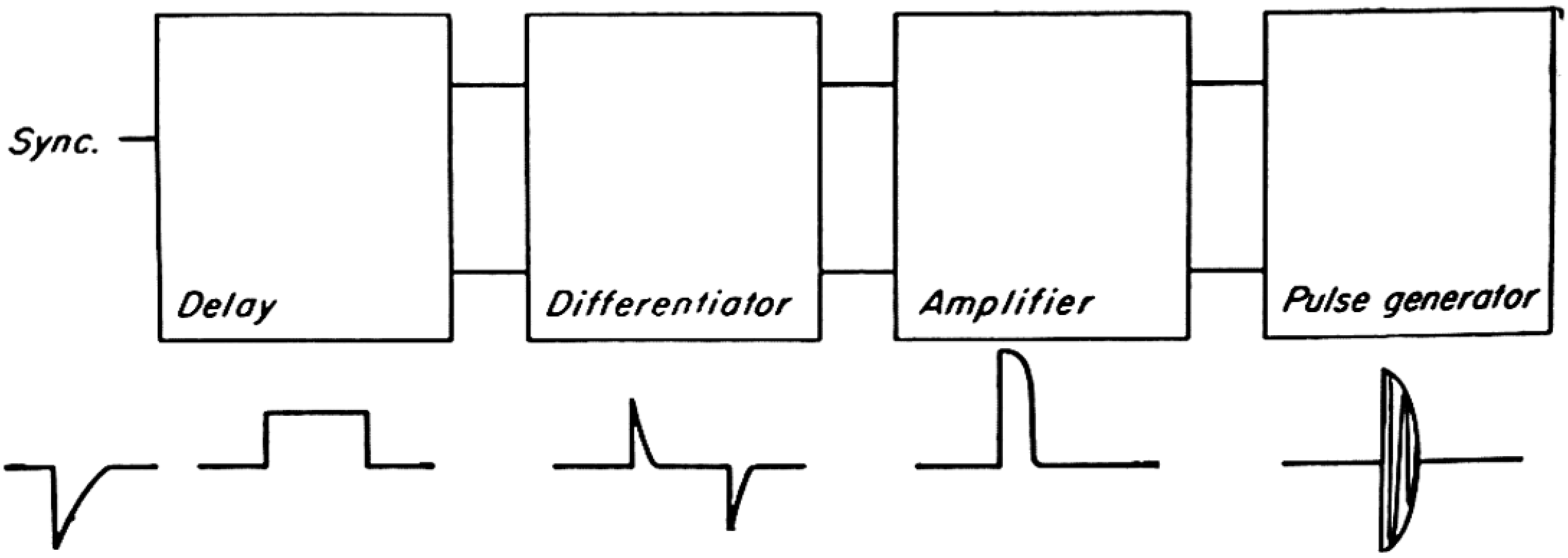


FIG. 7-20. Pulse-generator system.

Naturally, many circuits are capable of producing pulses. Those mentioned are illustrative only and in all cases the simplest possible ones.

Pulse generators may be of any kind and are usually classified as either hard or gas-tube types. Each has its own intrinsic advantages, largely determined by the particular application for which it is used. Since, in general, the high-vacuum tube may be either pulsed or continuously running while gas tubes can be only pulsed, and since there are a very large number of receiving and transmitting tubes that make excellent pulse generators, the hard type is slightly preferable, especially since it is not so erratic in action as the gas one and usually requires much less service.

Moreover, in certain cases the recovery time of the tube may affect the recovery of sensitivity of the receiver, particularly immediately after the pulse. All other things being equal, the high-vacuum tube is superior in this respect.

**Gas Tubes.** Any gas tube such as the 884, 2050, etc., can be use to provide pulsed oscillations. Also a number of thyratrons have been developed for radar work that can be used. Most of these latter types are of greater power-handling capabilities than needed in test work, but may be useful in some signaling application.

In all gas tubes the general operation is to maintain the grid negative and then trigger it with a positive pip. The tube will fire, as, for example, when used as a relaxation oscillator. If its plate current flows through a tuned circuit, this circuit will ring at a frequency determined by its own characteristics and for a period determined by its damping.

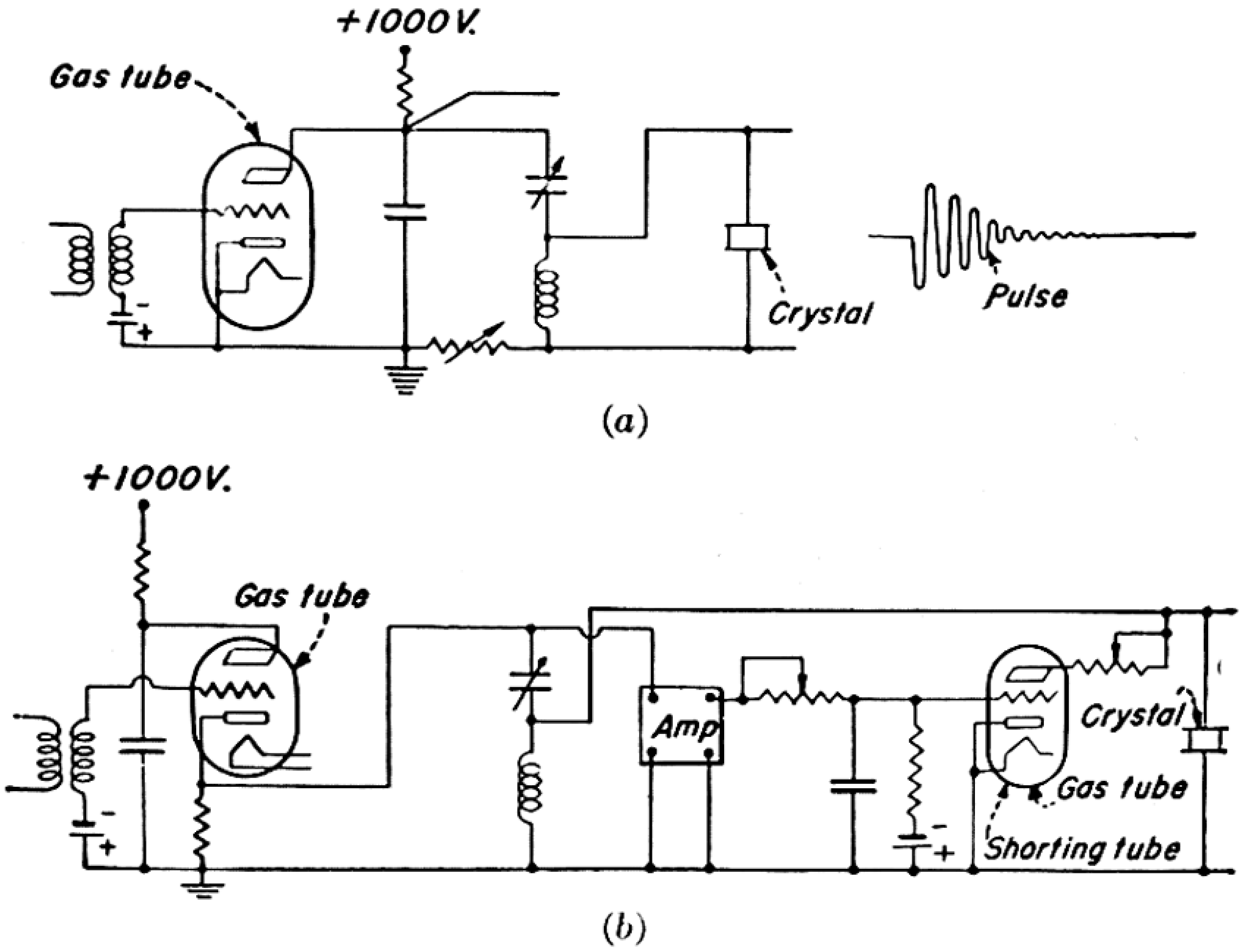


FIG. 7-21. Gas-tube pulse system: (a) without shorting tube, (b) with shorting tube.

If necessary, artificial damping in the form of additional resistance can be introduced either in series or in parallel so that the damping can be varied, together with the pulse length (and unfortunately the amplitude also). The resulting pulse will be exponential, since each successive sine wave will be smaller in amplitude than its immediate predecessor, because of the losses already mentioned. An illustrative system is shown in Fig. 7-21.[1] The output pulses produced by this oscillator are represented in Fig. 7-22.

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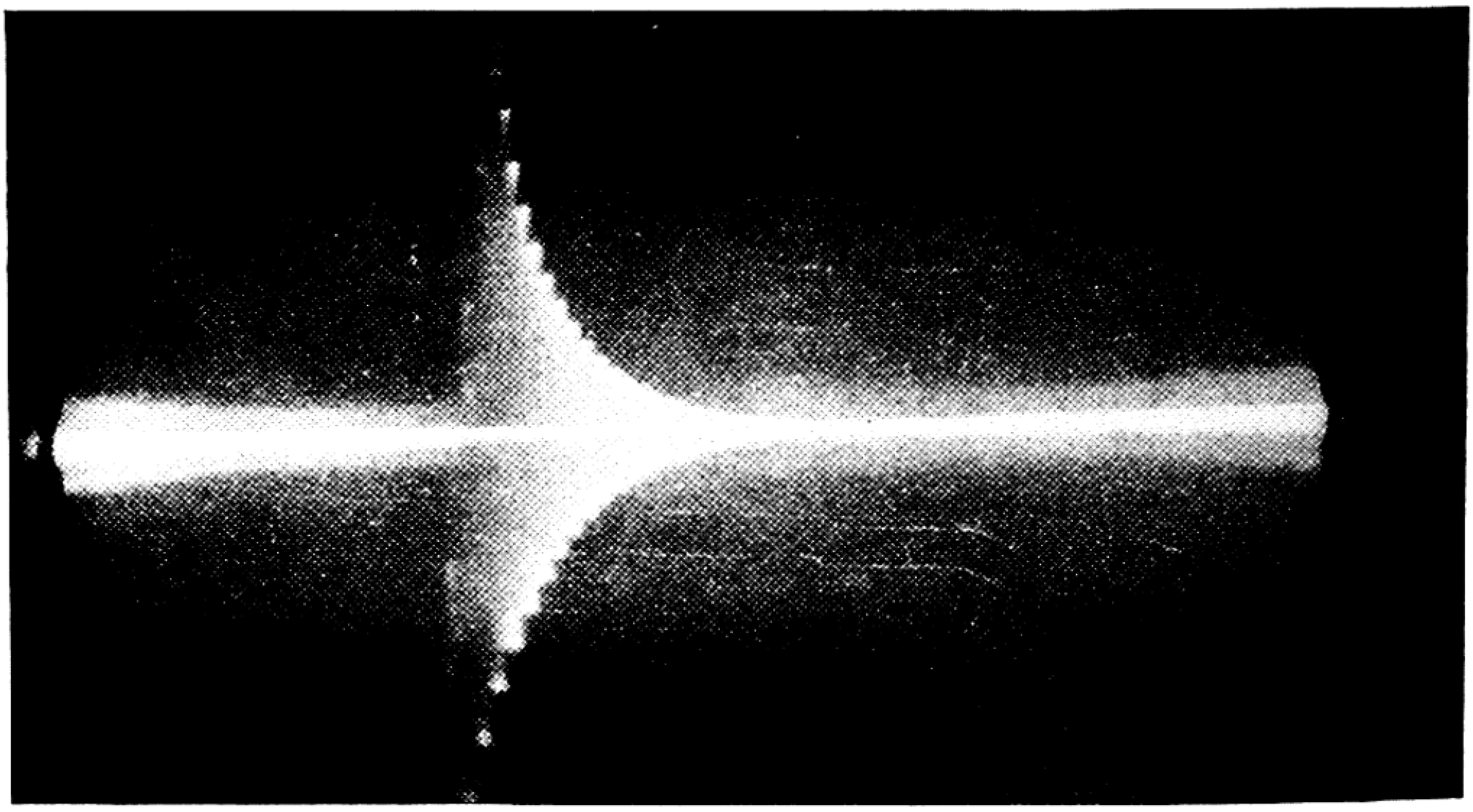
[1] F. A. Firestone, U.S. Patent 2,398,701, April 16, 1946.

An additional condenser may be connected into the plate circuit of the tube, where it will charge up and then discharge through the tube, further exciting the ringing circuit.

The Firestone patent discloses an additional variation. A complete train of damped waves is often undesirable. It may, for example, be better to have several large waves followed by essentially no oscillation. The small waves at the end of an exponential pulse contribute little to the pulse power in any case.



(*a*)

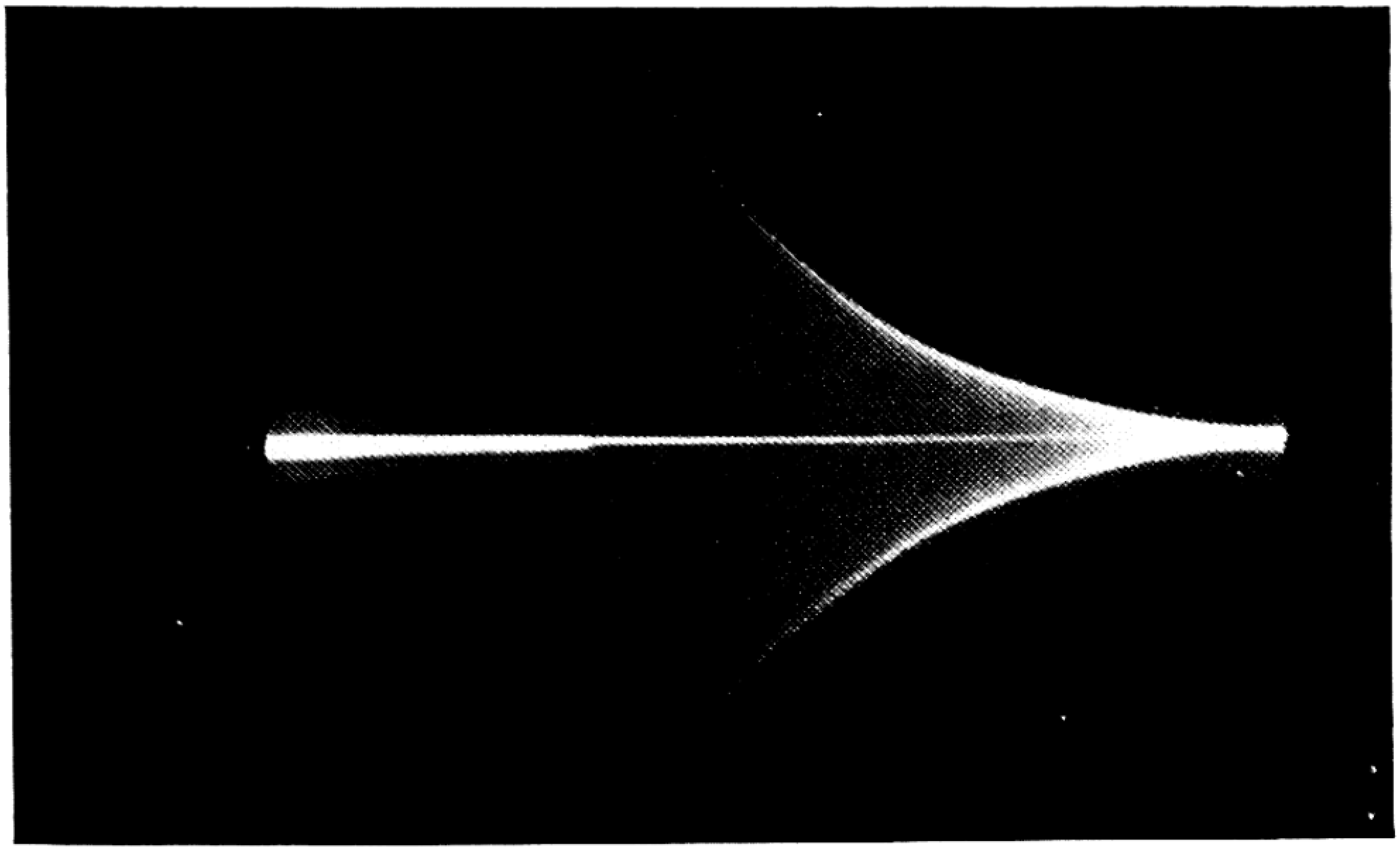
FIG. 7-22. Pulses: (*a*) damped, (*b*) undamped.

In order to cut off these small waves, a cutoff tube can be used and may be another gas tube, such as a second 884. This tube can be connected across the tuned circuit (Fig. 7-21). At an arbitrary time after the pulse is fired, the tube is tripped and shorts out the tuned circuit, thus stopping the oscillations suddenly.

Again, in this case, the recovery time of the tube is of great importance, since the resonant circuit in a pulsed reflection system is connected directly across the input receiver unless special circuits are used. If the cutoff tube has a long recovery time, the receiver will be unable to receive signals close to the pulse.

Gas tubes can also be used to trigger hard ones. This method was fairly common in radar systems.

Gas pulse oscillators have been widely and successfully used. They are simple and economical but erratic in action. The tube itself often produces extraneous signals, and each tube may act differently even in a group bought at the same time from the same manufacturer.



(*b*)

As already indicated, the duration of the pulse in a gas-type pulse generator is essentially independent of the synchronizing signal and is controlled only by the decay time of the tuned resonant circuit. Variable resistors added to this circuit will make the duration adjustable. About 0 to 500 ohms is satisfactory when the resistor is in series with the coil and about 0 to 25,000 ohms when in parallel.

**The High-vacuum Pulse.** High-vacuum tubes can also be used to produce pulses in any one of a number of ways. For example, they can be used to shock excite a resonant circuit in the same manner as the gas tube just described. In such a case they may either start or interrupt a high current flowing through that circuit. The latter is the more common arrangement. Figure 7-23 is a typical hard-tube shock-excited oscillator.

The tube that acts as the switch may have the tuned circuit anywhere in the path of its plate current. If the grid is held positive by returning it to a suitable voltage, the tube will conduct very heavily and the resulting current flow through the tank inductance. A large negative pulse is then applied to the tube grid, cutting off the current and shocking the resonant circuit into oscillation. This operation has already been described in the section on pulse forming.

The number of cycles of oscillation will depend on the length of the triggering signal and on the damping in the circuit. Since the tube acts as a switch, it does not influence the frequency of oscillation.

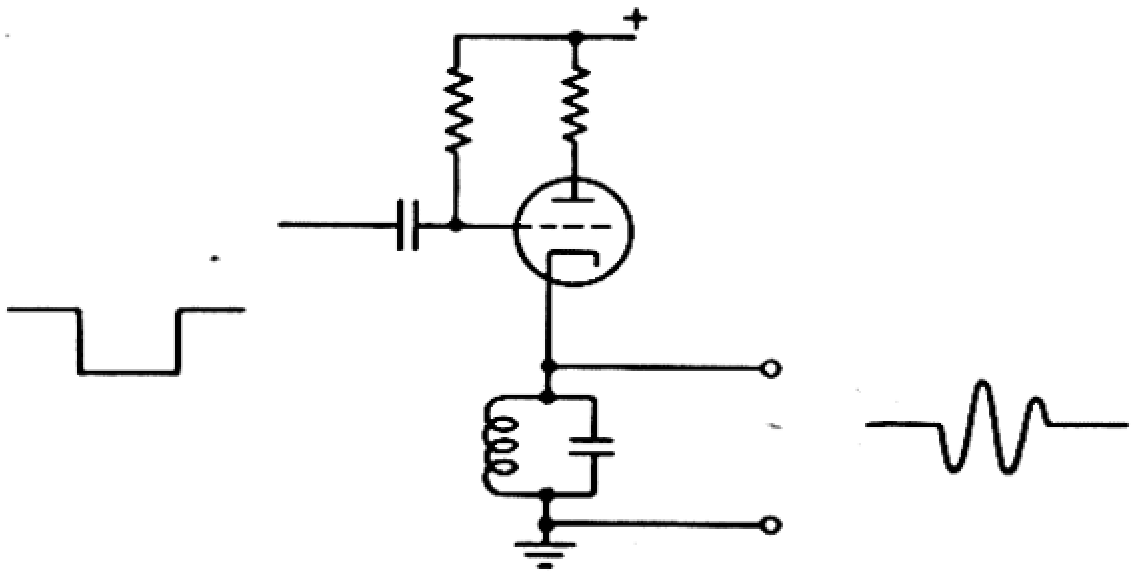


FIG. 7-23. Ringing oscillator.

When the trigger ends, however, the tube rapidly returns to the state where it is conducting heavily and the oscillations abruptly stop, owing to the shunting effect of the tube.

Other types of circuits are also possible. Possibly the simplest method is to have an oscillator of any of the familiar kinds, *e.g.*, Hartley, with a huge negative grid bias to keep it from oscillating. The trigger pulse is then used to remove this bias and allow the tube to oscillate. The triggering pulse may, of course, be either delayed or not in the usual manner.

The oscillator should be so designed that it is self-starting, and oscillations should build up quickly. Normally, the first half cycle is extremely large owing to transient effects, so the rapidity of starting is not a difficult problem.

When the trigger is removed, the pulse should cut off immediately. This does not always happen, and the oscillator may continue to ring for a few cycles. This is not of any consequence, since damping may be introduced to stop it quickly. The oscillator usually builds up in about ½ cycle and stops entirely in 1½ cycles.

It is more troublesome when the oscillator stops before the end of the trigger signal, since the end of the gate itself may produce spurious signals on the indicator.

The schematic of a conventional Hartley-type oscillator is shown in Fig. 7-24. If the cable to the crystal is directly across the tank circuit, without special coupling means, it must introduce very little capacitance into the current. The tank should also be designed to resonate with the tuning condenser as close to all the way out as possible; *i.e.*, the coil and its distributed capacity should resonate at a frequency very close to that desired. The minimum capacity controls the range over which it is possible to tune the circuit.

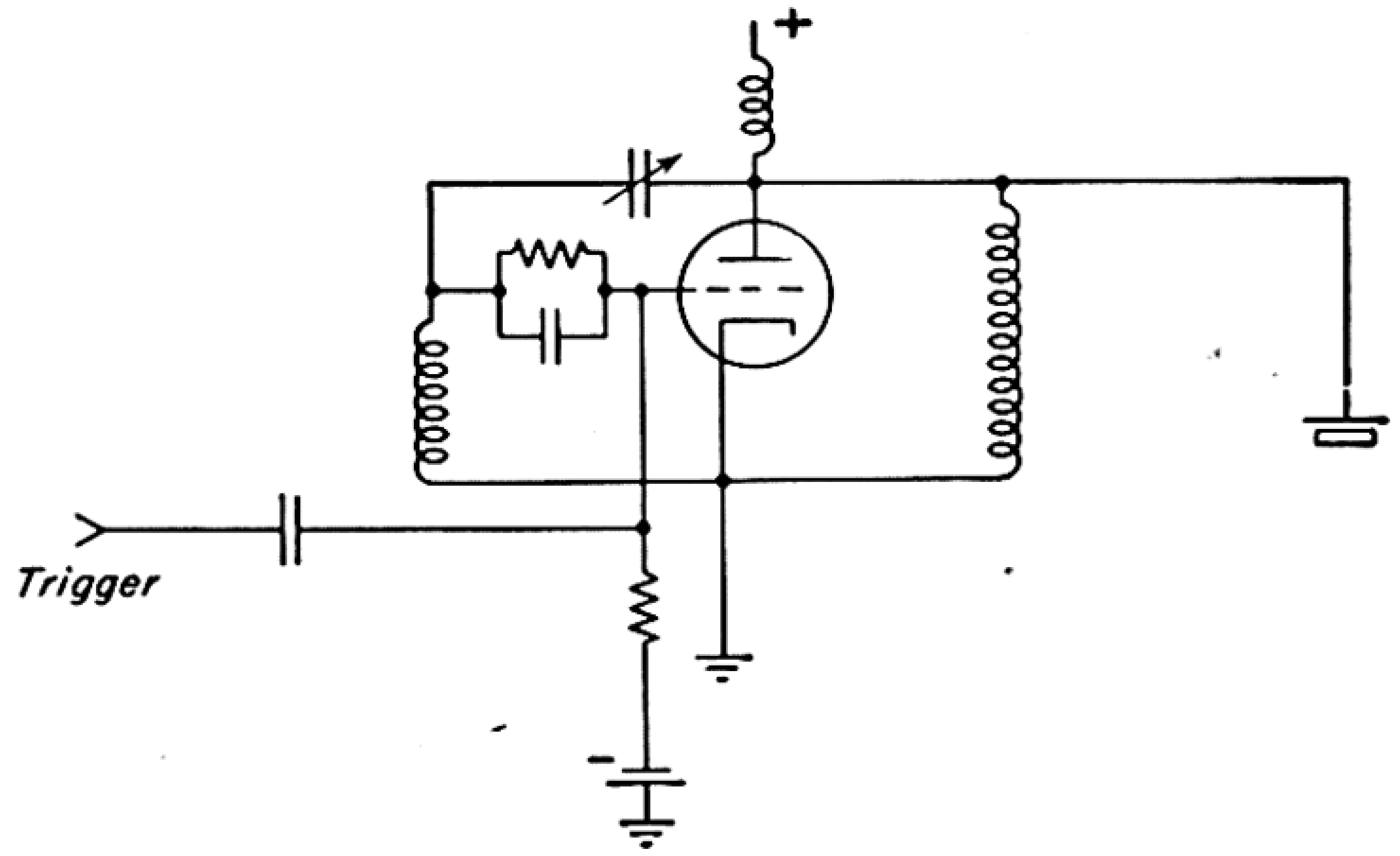


FIG. 7-24. Triggered oscillator.

As far as sensitivity is concerned, connecting the cable directly across the resonant circuit is satisfactory. If any direct voltage is present, it must be blocked out by a suitable condenser.

Adjustment of either the grid leak or bias voltage will prevent any tendency the circuit has to multiple fire.

The oscillator can be modulated on any electrode. However, for one-tube systems, the results are satisfactory when the control grid is used, and the amount of power required to pulse the oscillator is usually less than with other methods. Moreover, it is easier to keep the impedance of the circuit into which the triggering pulse is fed high enough to prevent deformation of the control voltage.

Low-level oscillators can be easily pulsed and then followed by several stages of radio-frequency amplification. Such systems have the advantage of greater stability and more output but require more space and parts than the one-tube variety.

A Hartley, such as the one described, can be made self-pulsing by a change in its components. This is explained in the following manner: If the grid leak and condenser has a sufficiently long time constant, the condenser charges up on each cycle, but this charge cannot escape entirely between cycles. Finally the charge on this condenser becomes so large that oscillations stop entirely. The oscillator then quits until enough charge drains off so that it can again operate. Thus pulses of oscillation interposed with longer periods of no oscillation result.

The period of oscillation is the time during which the condenser is charging and is therefore determined by condenser size. When the capacity is small, the pulse is accordingly short, and vice versa.

The time between pulses is determined by the total time constant of the resistor and condenser. When this is large, the time between pulses is also large, since the charge takes a long time to leak off.

Self-pulsing oscillators are somewhat more difficult to synchronize than other types. However, they can be synchronized, or the sweep can be synchronized from them. The self-blocking characteristic can also be used in conjunction with other types of operation to get sharper cutoff.

One of the chief advantages of a hard-tube generator is the fact that the successive waves are all of about the same height; *i.e.*, they are not exponentially damped.

**Ultrasonic Receivers for Pulsed Energy.** Amplification of pulse-type high-frequency signals requires an amplifier of great band width in order to have satisfactory resolution. The term *resolution* refers to the ability of a system to distinguish among signals following very closely upon one another. This property of an amplifier is directly dependent upon its band width.

In other words, the more closely together the signals fall in time the greater will be the band width required to distinguish them. If they are, for example, 1 $\mu$sec apart, a band width of

1 mc is required; if they are ¼ μsec apart, a band width of 4 μsec is necessary. This relation is therefore a fundamental one; *i.e.*, the resolution is the reciprocal of the band width.

$$R = \frac{1}{BW}$$

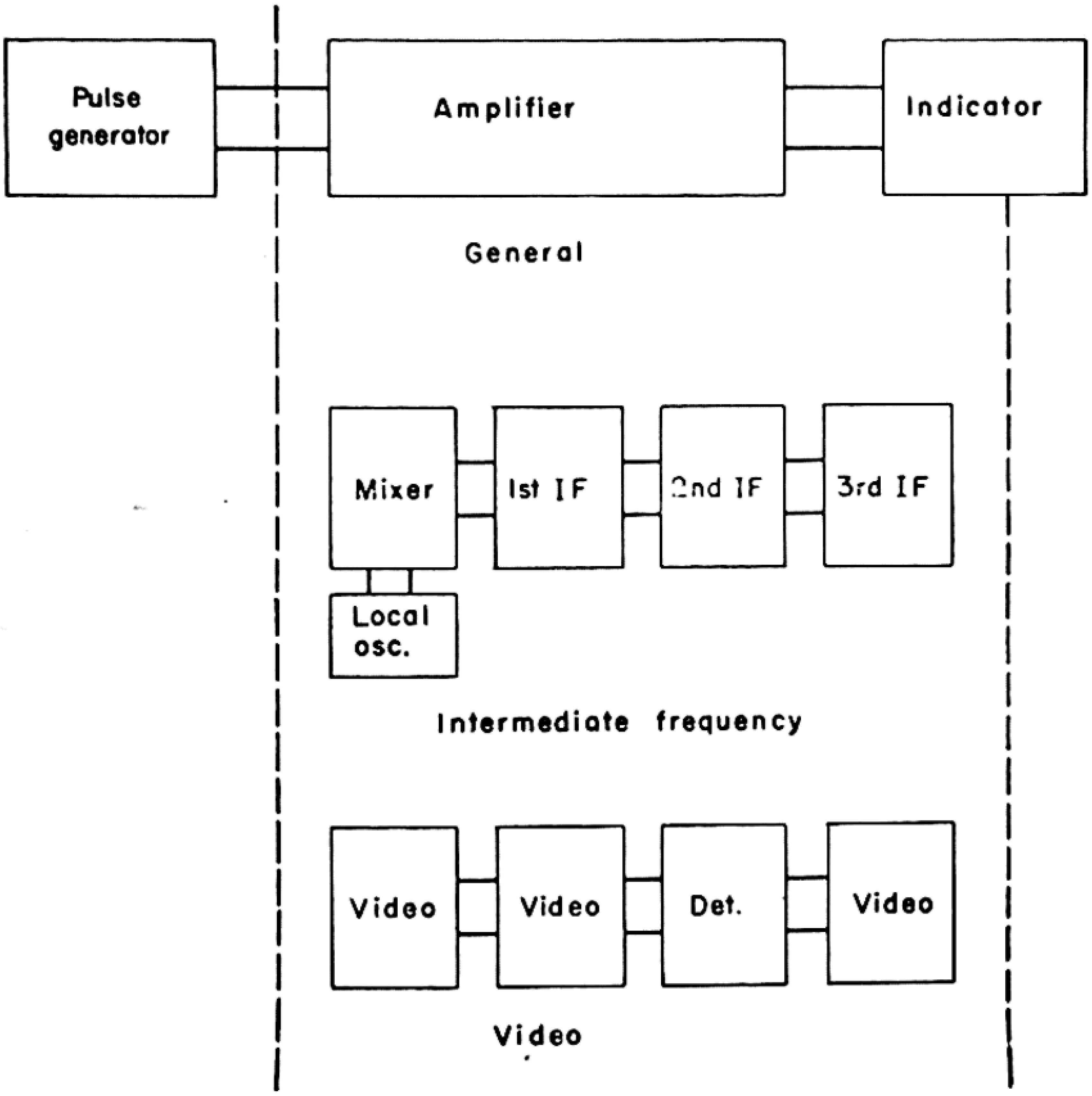


FIG. 7-25. Ultrasonic receivers.

Generally, a band width of 1 mc is sufficient for most ultrasonic testing systems, although for greater resolution, ones of as great as 4 mc may be used. However, it is not usually necessary to distinguish the cycles of high frequency in a signal. All that is required is the resolution of the envelope, and signals closer together than 1 μsec are rare.

The amplifier may be of two basic kinds, *i.e.*, superheterodyne or video. These two systems are indicated by the block diagram (Fig. 7-25). The main difference is that in the superheterodyne receiver the signal is changed to an intermediate frequency by mixing with a local oscillator voltage while in the video it is directly amplified at the frequency of ultrasonic test.

Both systems are satisfactory and have worked excellently in practice. Whatever slight advantage there may be is probably in favor of the superheterodyne type. For one thing, as the frequency of operation becomes greater than about 5 mc, most video systems lose gain; and for another, it is difficult to keep video systems from oscillating.

The intermediate-frequency amplifier is well known in television work, where very similar requirements must be met. An amplifier with a band width of 2 mc or more, center frequency of about 10 mc, and gain of 10,000 is satisfactory. Three or four intermediate stages will provide this.

Where the local oscillator must run very close to the frequency of the amplifier band pass, such as in the case where the testing frequency is very low, a reject circuit must be provided to sharpen one side of the pass characteristic and make it fall off more quickly than it would otherwise. Rejects are also well known in television, where they are used to keep the audio signals out of the picture. They may take the form of series traps, resonant circuits in the cathodes of the tubes, etc.

The local oscillator is of the conventional type. It is generally advisable to use a separate mixer and oscillator rather than a single tube. The oscillator may operate either above or below the intermediate frequency. Operating at the lower frequency has some advantages in gain.

One of the greatest difficulties in pulse transmission and reception is the effect the pulses have upon the input of the receiver when they are impressed directly across it. However, if only one crystal is to be used, there is no other simple way of connecting the circuit. These effects are likely either to block the amplifier totally for a time that is appreciable in comparison with the time of transmission and reflection or to produce extraneous signals, such as long tails on the pulse, which have the effect of blotting out the received signals. Because of this blocking, it is very difficult to receive signals close to the surface from which the pulse is being transmitted. As the distance between transmitter and reflector gets shorter and shorter, the problem becomes more and more difficult.

The most obvious expedient is to place a very low time constant in the input stages so that signals will not block them for any appreciable time. Keeping all condensers and resistors as small as possible will accomplish this. Unfortunately, it also has the effect of sharply lowering the gain.

Keeping the voltage supply to the tubes regulated will also facilitate recovery. Moreover, certain specialized procedures and circuits may be resorted to in order to stop the blocking of the amplifier.

Possibly the simplest method of avoiding the problem is the use of separate transducers for sending and receiving. This will provide a great deal of improvement, since only stray electrical coupling will remain to bring the initial pulse into the receiver. However, it makes necessary the use of separate cables and crystals. The desire to avoid this complication has resulted in the use of concentric or side-by-side crystals, which can be set in a single mount and connected by two separate cables to the receiver. However, the capacity between such cables may lead to additional undesirable coupling. The much greater simplicity, economy, and ease of single-crystal work has led to its widespread adoption and the minimizing of blocking by various types of special circuits.

**Methods of Gating the Receiver.** Gating refers to turning a system on or off according to an arbitrary signal. Signals may be used to render an amplifier insensitive, so that troublesome indications will not pass. This system has certain drawbacks; *i.e.*, the gating signal must be of the same size as the signal it is to stop, and it may therefore cause transient effects of its own. Its duration must be closely controlled, since it will otherwise block out signals that are wanted. Any method for producing these gates can be used, and they may be of either polarity.

For purposes of illustration, some connections for gating procedures are briefly illustrated (Fig. 7-26). In the first instance a tube is inserted between the pulse generator and receiver, and its impedance varied so that it is very high during the transmission of the pulse and very low at all other times. This has the desired effect of discriminating against the pulse and in favor of the reflections.

In the second case the tube acts as a grid resistor, which can be varied to place various amounts of negative bias on the amplifier tube and thus cause it to allow signals to pass or not.

A number of gas-tube applications have been suggested. Inasmuch as the same problem was intrinsic to radar, the TR and anti TR boxes were developed for the same purpose. In those cases, cavities filled with gas were used. The gas broke down during pulse transmission, because of the high associated radio-frequency voltages, and short-circuited the receiver input. The radio-frequency pulses associated with ultrasonics transmission are not sufficiently great and of high enough frequency for use with those TR devices which are available. Use of conventional gas tubes such as the 884 has been suggested, but the time of ionization and deionization is always high, and hash is introduced by erratic behavior of the gas.

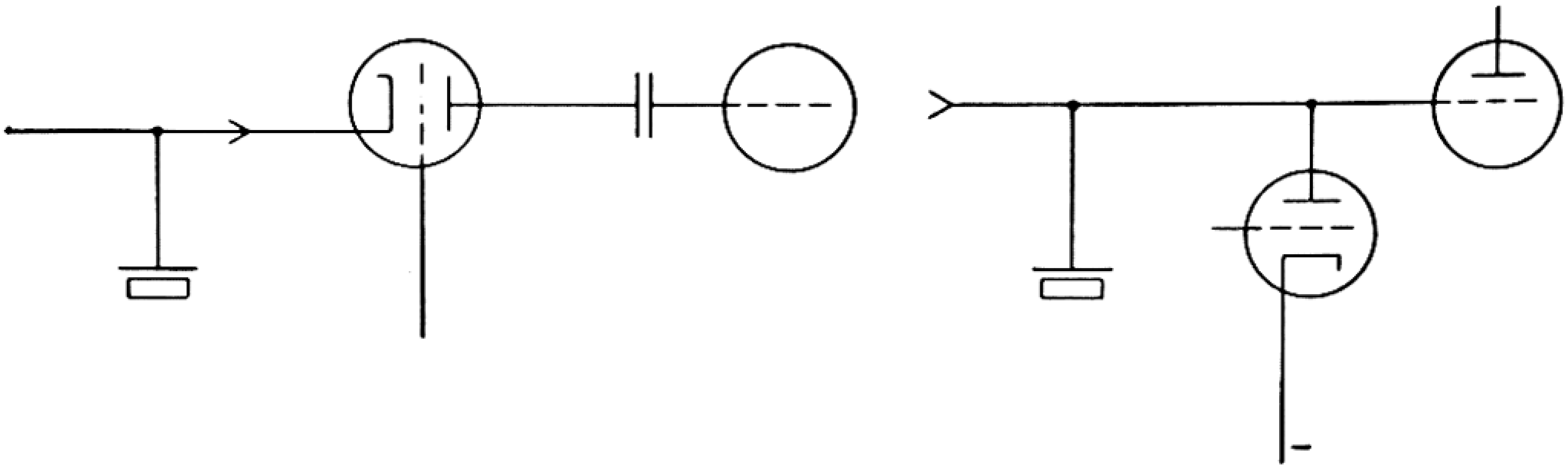


FIG. 7-26. Gating circuits.

The gating signal must usually be higher than the radio-frequency pulse itself, and this is difficult where about 1,000-volt, 1- or 2-$\mu$sec pulses are used. For this and other reasons, gates with simple ultrasonic signals have not been very successful to date.

**Some Considerations in Ultrasonic Testing.** A number of problems arise in pulse testing besides rapid recovery and measurement of small time intervals.

The appearance of the reflected pulse often varies. In certain cases a strong reflection will return first, and between that reflection and the next one there will be a series of minor reflections. These are due to parts of the energy that travel through the media in other directions or by other paths than the initial reflection. The spacing between these reflections seems to be a function both of the part's thickness and of Poisson's ratio. However, the pattern is sometimes so confused that it is difficult to interpret. These reflections are also due to transformations of the wave energy between *S* and *L* types.

When testing a part for defects, secondary reflections are ordinarily ignored, and luckily no such reflection occurs before the first large reflected pulse, which is the primary measure of time.

Moreover, that first large reflected pulse may itself seem to consist of a large pulse closely followed by successively smaller ones. Sometimes it appears to be a succession of three or four pulses each of which is a trifle larger than the preceding one. The exact analysis of these variations is extremely difficult because of the complexity of the situation. However, when nothing but time is being measured, it makes little difference.

Sometimes surface-wave reflections occur, together with the others. Running the fingers gently over the surface may show the points of maximum occurrence and, if waves are set up in the couplant on the surface, will tend to eliminate them.

# CHAPTER VIII

## ULTRASONIC AGITATION

Agitation by sonic or ultrasonic means is well known in certain fields, especially the chemical one. Generally, ultrasonics is more readily usable than audible sound because it is more easily generated at suitable intensities and because the order of wavelength is smaller. High frequencies are more readily absorbed in the agitated systems; whether or not this is desirable above a certain point is questionable. However, when the frequencies are about 1½ mc, this factor becomes appreciable.

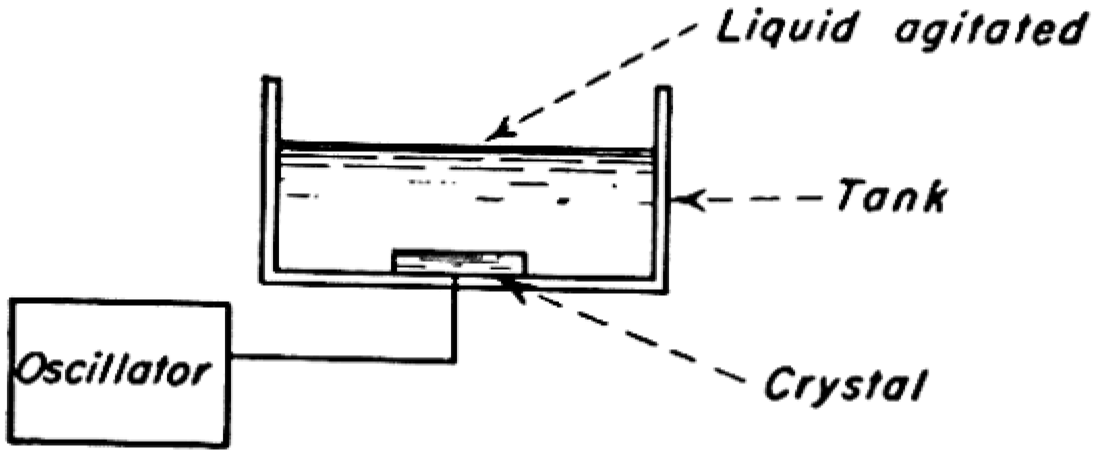


FIG. 8-1. Ultrasonic agitation system.

The field of ultrasonic agitation is one of the most promising ones. At first glance, it would appear that by this means far-reaching changes in matter might be accomplished. Nevertheless, although many theoretical investigations have been carried out in the laboratory, little work has been done toward applying the phenomenon to problems of industrial scope. A number of ultrasonic agitators have been presented commercially from time to time. All are essentially similar and as far as known perform more or less in the same fashion. However, the basic work of the original investigators is still the main source of extensive information on the effects of radiation and its applications.

The basic form of the ultrasonic agitator is shown in the block diagram (Fig. 8-1). A high-power oscillator produces radio-frequency energy, which is impressed upon a suitable crystal that sends very powerful ultrasonic waves through the material, usually a liquid held in a tank or container. The waves then react upon the liquid. When a solid is to be agitated, it is immersed in the liquid and treated in the same fashion.

Another common method is to place the liquid or liquids to be agitated in a test tube or other separate container. This is then immersed in the liquid, which actually carries the ultrasonic waves and which is kept entirely separate.

**General.** Ultrasonic vibrations of great intensity bring about astounding changes in various forms of matter. Work has been carried out in the biological, physical, and chemical fields with such effects; and although the application is in its infancy, it appears to offer great possibilities to the experimenter.

The function of this discussion will be to indicate briefly some of the more outstanding phenomena. Generally speaking, more emphasis will be placed upon the apparatus necessary for production of the ultrasonic waves than upon specific effects.

Ultrasonic oscillations for the purposes of agitation are generally produced by electronic oscillators, which drive individual quartz crystals or mosaics of them into strong vibration and couple this vibration into a liquid. Special crystal holders must be used for such applications and have already been described.

Frequencies that have been used in the past in this type of work have been in the lower ultrasonic order and have ranged from 100,000 to 1,500,000 cycles. Frequencies as great as 5 mc have been used. As the voltage that is impressed on the crystal becomes greater and greater, flashover is more likely to occur unless the crystals are sufficiently thick, *i.e.*, therefore of low frequency. Moreover, the thinner and therefore higher frequency crystals are much more likely to fracture.

Ultrasonic waves have been found to cause pressures so large that the resulting mechanical stresses may be as great as 15,000 times the hydrostatic pressure. The acceleration of a crystal driving such a bath is extremely great and may reach 20,000 km/sec,[1] but the motion associated with such action is extremely small (a very small fraction of 1 mm). The crystal will build up to maximum velocity in a fraction of a microsecond.

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[1] R. W. Wood, "Supersonics," Brown University, 1939

The energy generated reaches a maximum when the distance between the face of the transducer and the top of the liquid is a whole number of half wavelengths. This can be seen physically, since in that case the phase relation is such that the successive reflections of the energy are additive. Under such conditions large values of amplitude may occur. For any one tank of liquid there are a great number of depths that will give this condition; any one of them can be used and more rapid ultrasonic effects obtained than when the relation does not obtain.

Wood reported a pressure of 150 g against a glass disk 8 cm in diameter and the projection of oil drops 30 or 40 cm above the surface of the liquid. Generally he worked with as much as 50,000 volts and at frequencies between 200,000 and 500,000 cycles.

**History.** The first experiments with modern high-power generators seem to have been carried out by Langevin, in his work already referred to in the development of an efficient means of locating submarines. His compound oscillators gave a method of generating high-intensity beams of ultrasonics, and during his experiments with the Poulsen arc he apparently noticed the lethal effect of the ultrasonic waves upon small marine life. Moreover, the heating, as well as the cavitation effects of the waves, was mentioned.

Langevin also originally noticed the fact that much greater powers were available for use under conditions of resonance, and he emphasized the necessity for tuning his oscillators to that point.

Various experiments followed the Langevin ones, but the greatest contribution next made seems to have been the collaboration of Wood and Loomis,[1] who carried out extensive experiments with a specially designed vacuum-tube generator (the Poulsen generator then being obsolete).

The conditions of frequency and voltage under which they worked have already been mentioned. Langevin had been interested only in long-distance propagation in liquids, which had limited the frequencies he used to a maximum of about 40,000 cycles because of the great absorption at higher frequencies.

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[1] R. W. Wood and A. L. Loomis, The Physical and Biological Effects of High Frequency Sound Waves of Great Intensity, *Phys. Rev.*, (2), **29**, 373 (1927).

In agitation work, of course, this is no problem, since there is very little liquid to travel through and therefore little absorption.

The oscillator was one designed for 2,000-watt output, operating through step-up transformers for greater voltage. Figure 8-2 shows the schematic of the unit. The crystals were disks and rested on a piece of lead placed at the bottom of a container of oil. A second electrode was placed on top of the crystal in the form of a circular piece of very thin brass sheet. This work was also the basis for the ultrasonic interferometer discussed elsewhere (under resonance).

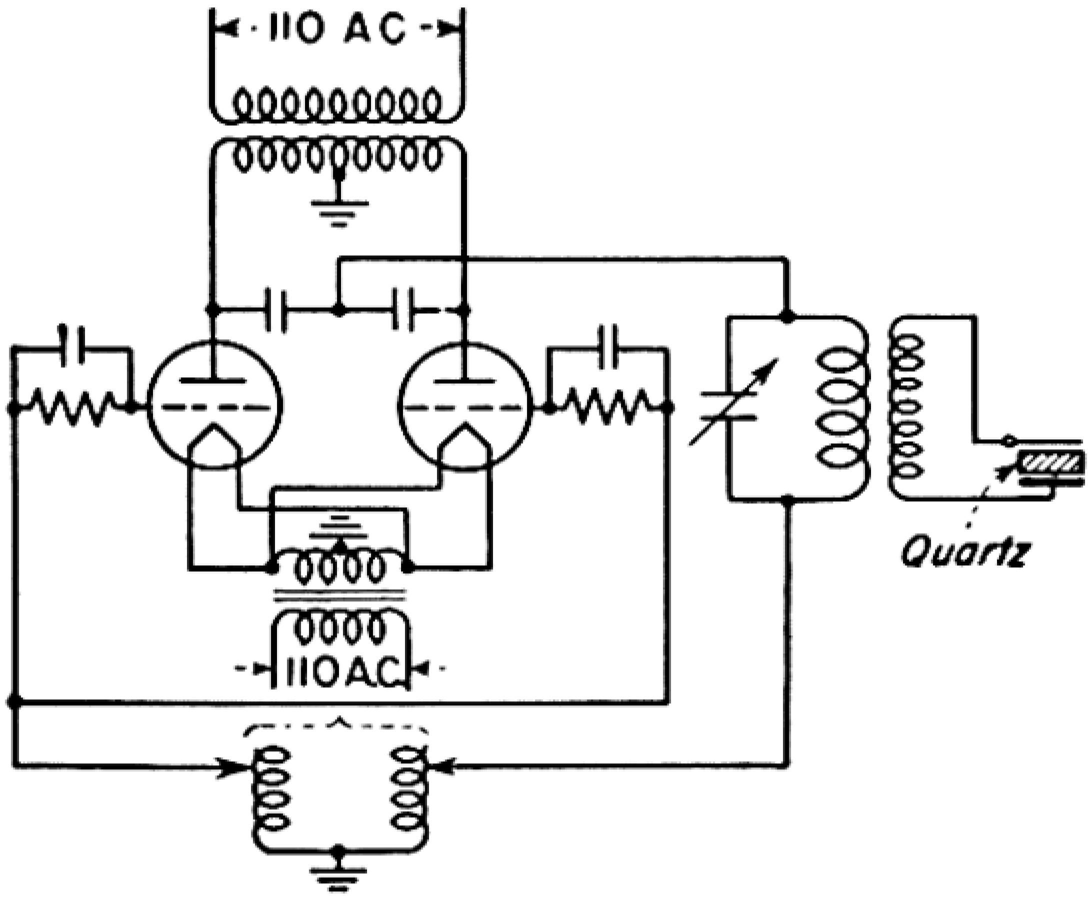

FIG. 8-2. Oscillator.

The action of the ultrasonics upon the liquid in a tank or beaker has been extensively described in the literature. At the interface between the liquid (usually oil) and air, the waves fling the liquid up into the air in the form of fine drops. This is usually demonstrated with benzoil, which produces a white fog. However, this only occurs at high powers. Generally very low power produces an irregular mound or group of mounds over the crystal. The mounds gradually become higher and higher as power is added and resolve into a single large, *i.e.*, high, mound. The resultant mound then becomes narrower as the frequency increases. The size of the drops flung up is a function of frequency to an extent; at low frequency they are large and irregular; and as the frequency rises, they gradually resolve into a fine mist. This occurs at about 2 mc. A fountain approximately 7 cm high should exist when action such as emulsification is taking place within a liquid. Jets 10 to 15 cm high are common and occasional drops may be flung up 30 or 40 cm. If such a mound or fountain does not exist, probably not enough power is being sent into the system to bring about the desired effects. The growth of these mounds is also connected with resonance in the proper dimension of the liquid, as already mentioned, and they are maximum at that point.

The container holding the liquid to be agitated is then introduced into the fountain at the point where maximum effect seems to exist and allowed to remain there while being treated.

As already mentioned, Sokolov investigated the various oscillators and frequencies from $10^4$ to $1.3 \times 10^8$ cycles, with special reference to the use in the metal industry for vibrating materials in their molten state. Work by this investigator is considered under crystals and holders.

**Generators.** Ultrasonic generators are essentially high-power oscillators such as are commonly used in radio work. The schematics for two such systems are shown (Figs. 8-3[1] and 8-4). There is nothing special about such oscillators except their extreme simplicity. The refinements necessary for radio-frequency generation for radio work can be discarded, while frequency stability, etc., is necessary for laboratory work only.

The primary purpose of such a generator is to produce sufficiently high-frequency oscillations at a high radio-frequency voltage. Langevin used a high-frequency arc (Poulsen) for his generator, but on the whole such methods have been entirely superseded by the oscillator (vacuum-tube type).

For application in air or gases, a Pierce-type oscillator may be used. That is, the crystal may be used both as a generator of ultrasonic waves and as a frequency-controlling device. When the crystal is used with liquids or solids, the damping effect is too great to allow this; *i.e.*, the oscillating quartz cannot maintain its own oscillations and control frequency at the same time. In air or gas, whistles or sirens can be used and also magnetostriction units.

Generators may be made to work from 20,000 to almost any required frequency, but the amount of power available from a

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[1] F. W. Smith and P. K. Stumpf, Ultrasonic Generator, *Electronics*, April, 1946.

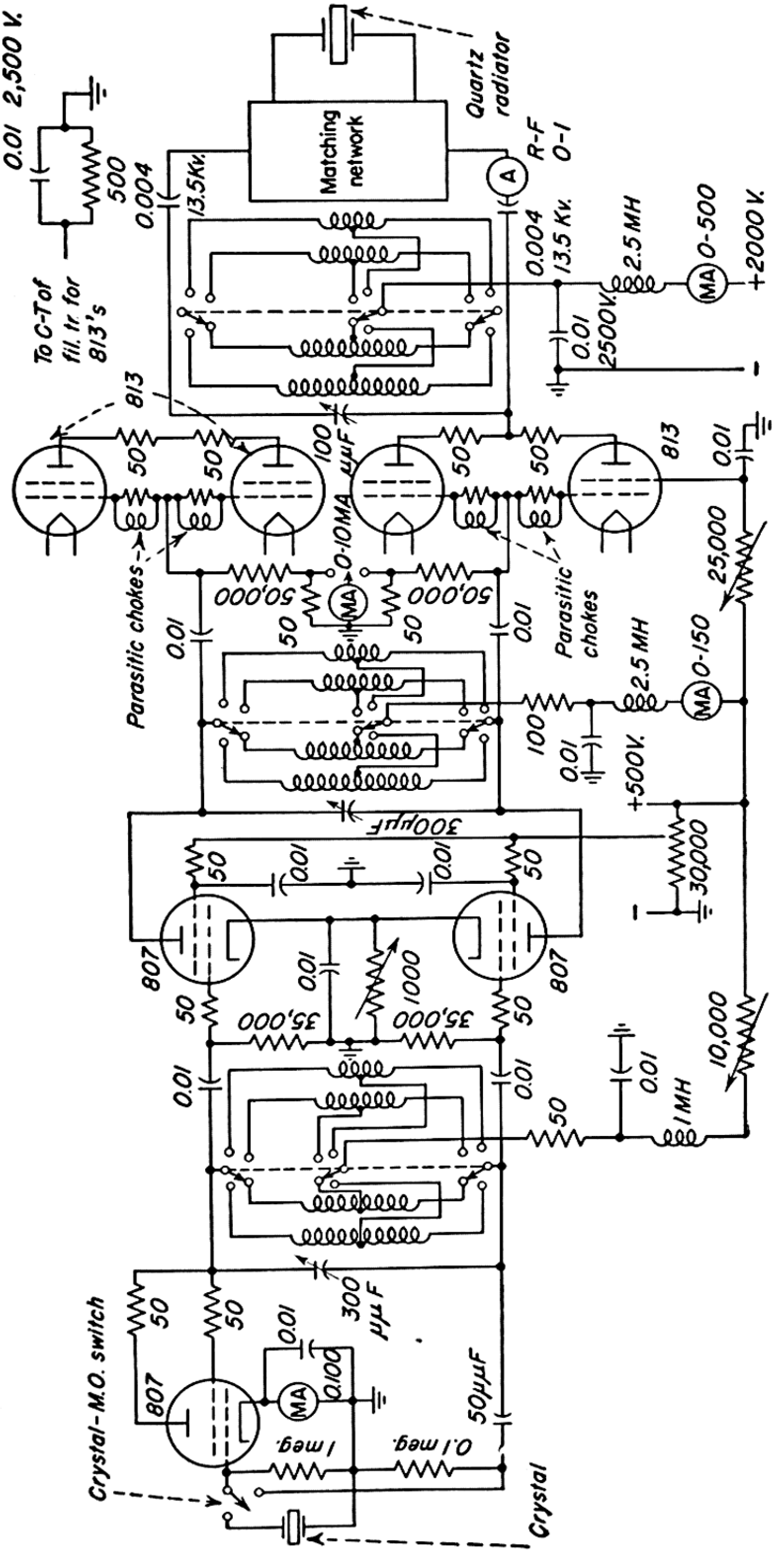

FIG. 8-3. Complete oscillator system.

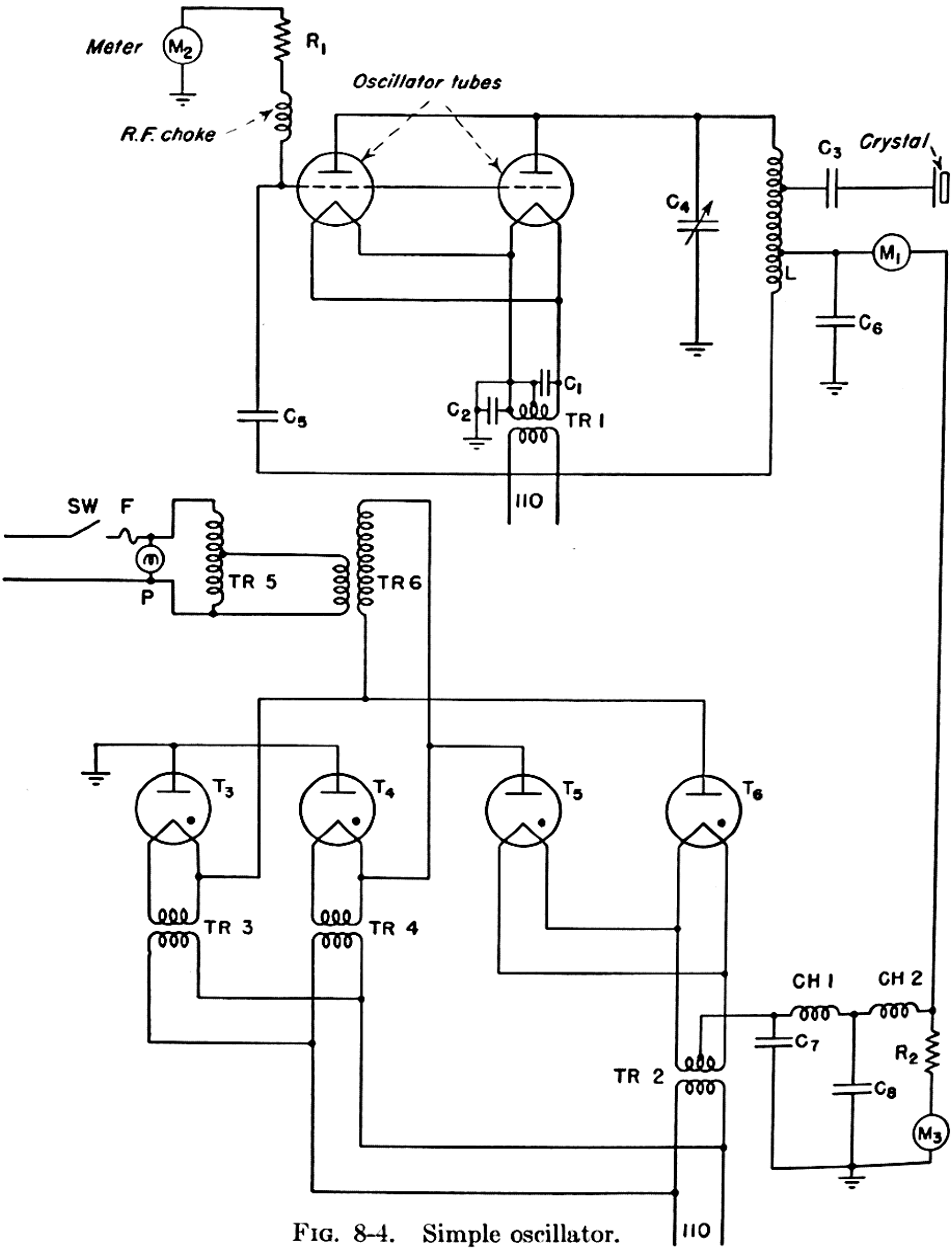

FIG. 8-4. Simple oscillator.

high-frequency generator is less because the quartz plate becomes very thin. For this reason, up to the present time most experiments have been performed at frequencies under a megacycle. Sonic frequencies are also occasionally utilized.

The frequency of generation can be controlled by a crystal or produced by any of the tuned types of oscillators.

Frequency sometimes causes a difference in the ultrasonic action. A particular effect may take place at a high frequency and not at a low one, etc. However, the exact relationship has not been worked out, except in a comparatively few specific cases.

A typical generator used in Japan[1] is shown in the attached schematic (Fig. 8-5), where $A_1$ is a d-c ammeter and $A_2$ a thermoammeter, $Q$ is the crystal, and $V$ a voltmeter.

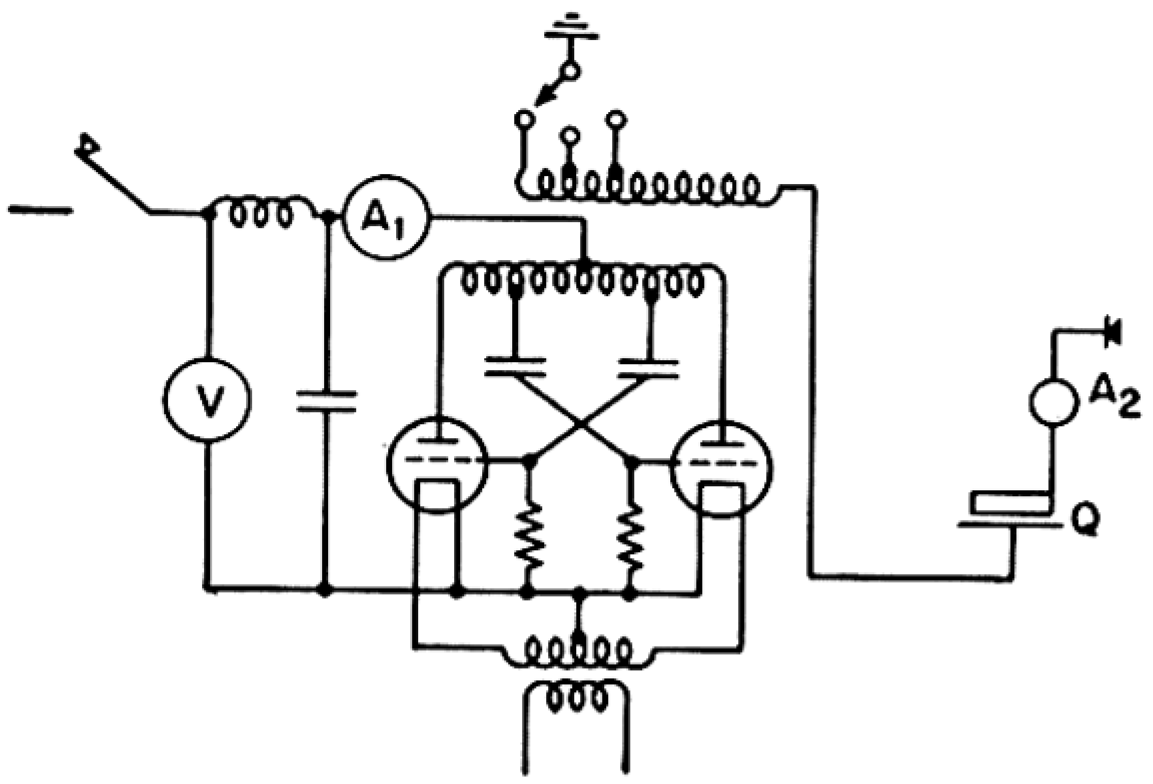

FIG. 8-5. Japanese oscillator.

An $X$-cut crystal with the following dimensions was used: The diameter was 3.5 cm, the thickness 6 mm, and the frequency 450 kc. The crystal surface was copper plated over silver. The lower electrode was a brass disk, which acted as the high-voltage contact and also was the support.

The output of the system was made greater by setting the brass disk at a thickness of an odd multiple of ¼ λ, causing it to reflect energy in phase and build up the oscillations. The experimenter inserted tinfoil between the crystal and the disk to tune it, *i.e.*, to build up the correct thickness.

The author measured his output both by a balance measure and by calorimetric measurement of the amount of energy absorbed by a piece of Bakelite 3 cm long.

Figure 8-6 shows the crystal and tank details for this apparatus. All apparatus of this nature has a strong family resemblance, and the one shown is accordingly very similar to apparatus produced in this country and in others.

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[1] H. Oyama, Generation and Application of Intense Supersonic Acoustic Waves, *Rep. Radio Res., Japan*, **4**, 41 (1934).

Coils can be used for coupling the crystal to the oscillator in order to raise the voltage to a sufficiently high value.

Piezoelectric transducers are most commonly used today, especially for frequencies between 0.1 and 1 mc. Magnetostrictive systems are usually constructed for any range below this (up to about 50,000 cycles) where the size of the transducer becomes too small to handle conveniently. The crystals for this purpose are about 75 mm in diameter and between 7 and 14 mm thick (for frequencies between about 0.1 and 0.3 mc). Compound oscillators constructed to produce the same frequencies can also be used.

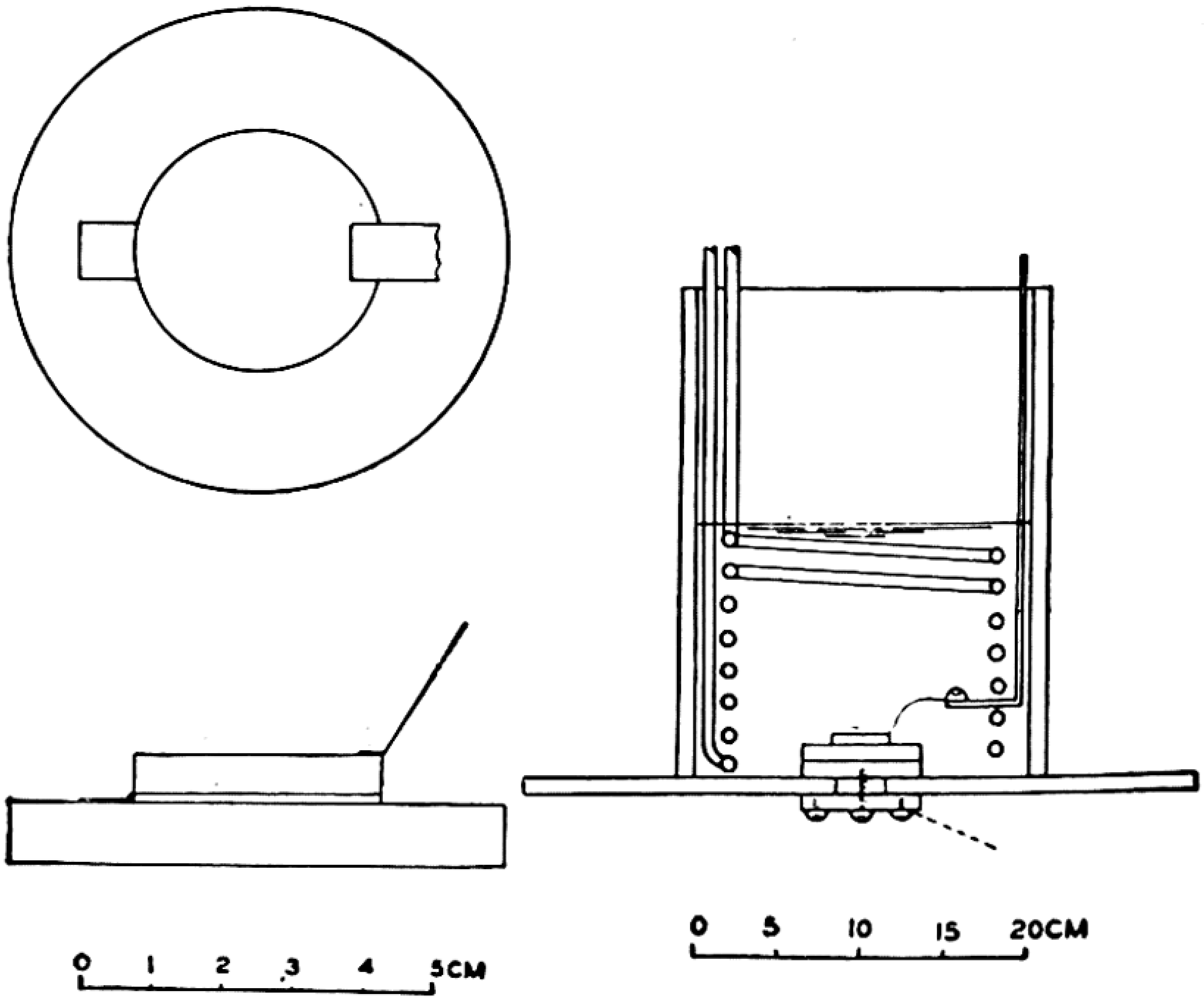

FIG. 8-6. Tank assembly.

The transducer is normally coupled to the oscillator by a transformer or Tesla coil. The output of the oscillator should be as great as possible and is usually a few hundred watts.

There should be some means of varying the voltage appearing across the transducer and also that across the primary of the coupling coil, as different voltages produce different effects. However, the output of the oscillator should be great enough so that agitating operation will not take a tremendously long time.

If the power output is too small, the desired effect will not be produced at all. The consensus of investigators seems to be that a minimum of several hundred watts is necessary and a crystal plate of more than about 50 mm minimum diameter should be used. Lower powers and sizes are unsatisfactory. The voltages on the secondary should be variable from about 30,000 to 60,000 radio-frequency volts.

**Holders and Containers.** Probably the chief difficulty in intense ultrasonic generation is the design of the crystal holder. Such holders are described elsewhere.

The problems in the mounting of the crystal are the possibility of electrical breakdown and the support of the holder and container in such a way as to permit the entry of maximum power into the media.

Another critical element is the possibility of mechanical breakdown. As indicated, the simplest type of support is to lay the crystal on a block of lead and place a plate of brass or other electrically conducting material on its face. This is essentially what was done by Wood and Loomis. The upper electrode may also be a brass ring, so that the waves can progress through the open center. The upper plate is held down by hooks or clips made of nonconducting material such as glass. The electrode should be as thin as possible for the greatest output.

When a test tube is dipped into the vibrating bath, it must be constructed of strong thin glass. However, the container's wall thickness is not critical, since the waves do not progress through the glass as *L* types only but more commonly as *S* types. Chemicals are treated in separate containers in this way, since they might damage the system electrically or mechanically if they were brought into direct contact with it.

Although the wave type is *S* during the transmission through the glass walls of the containers, only *L* waves exist in the liquids being agitated, since *S* types cannot exist in them.

The transformation of the ultrasonic waves takes place because of the angle at which the *L* waves strike the walls of the container. The theory pertaining to this action will be found elsewhere. However, although *S* waves will be produced in tall, thin test tubes because the energy strikes the walls at the proper angles, there will be no transformation in short flat containers, where the energy hits the bottom at normal angle. This may or may not be an advantage depending on the particular desires of the investigator. However, wall thickness may be critical with respect to $L$ waves. Figure 8-7 is a diagrammatic representation of this situation.

The use of focusing crystals and of air-backed ones has been suggested for agitation work, as well as that of compound oscillators. Naturally the damping of the crystal is as low as possible, and its faces are polished for greater output.

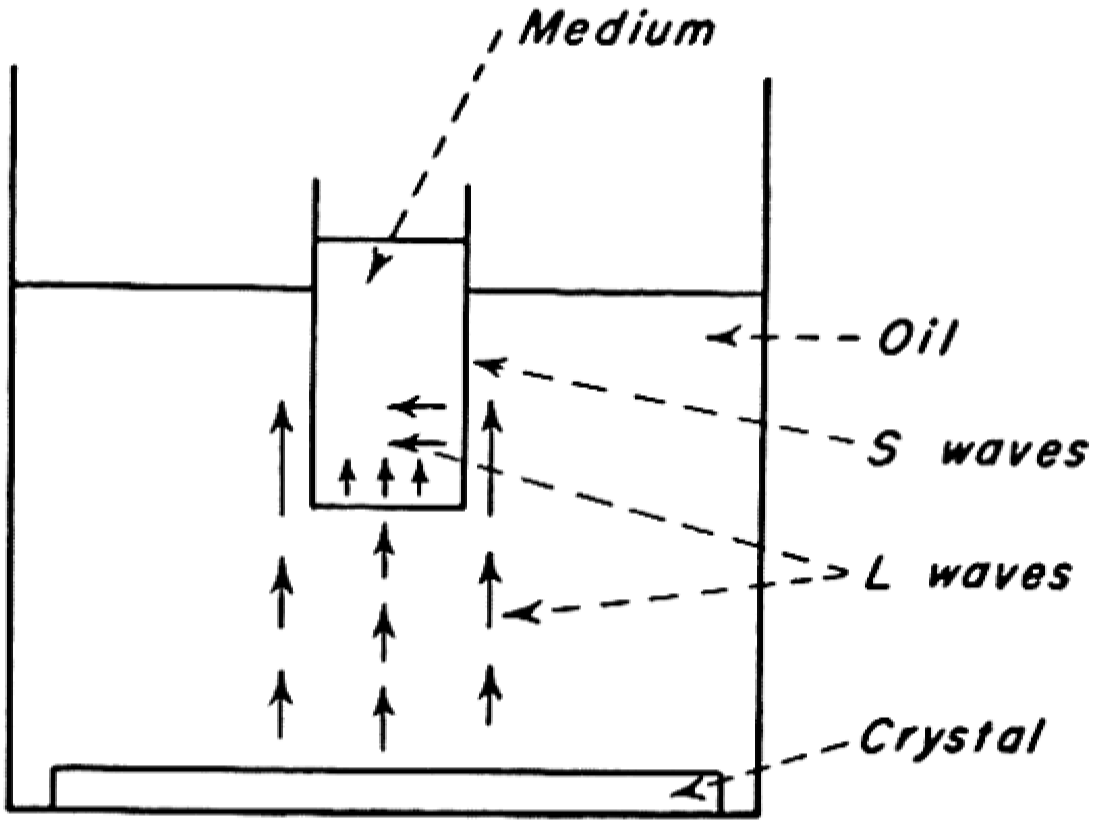

FIG. 8-7. Wave progression through test tube.

**Power Output.** Authorities in the past have disagreed about the maximum power output it was possible to get from a crystal, and figures from 10 to 37 watts/sq cm have been advanced as the maximum possible without shattering. However, it appears likely that greater powers are now possible and are a function of the mounting, medium, frequency, and unit design. The limit at which the crystal is destroyed can be minimized by matching the crystal impedance so that the voltage gradient is made a minimum and by holder design. Claims have been made for 43 watts/sq cm.

Breakdown appears to be an electrical phenomenon.[1] Calculation of the power-production capabilities of $X$-cut crystals operating in transformer oil appears to offer possibilities as high as $10^4$ watts/sq cm. On the other hand, the limit to the power output due to the lack of dielectric strength of the surrounding medium is fairly low; and once breakdown occurs, as in oil, the heat from the arc that results produces strains and resultant crystal failure. These arcs appear to occur in the oil alone, which has a dielectric strength of 100 or 200 kv/cm, while quartz has one of about 5,700 kv/cm for 0.05 mm.[1]

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[1] L. F. Epstein, M. A. Anderson, and L. R. Harden, High Intensity Ultrasonics, *J. Acoust. Soc. Am.*, **19,** No. 1, 248, January, 1947.

As indicated, many experimenters have used air backings to minimize oil breakdown and also because there is much greater reflection at the back surface of the transducer and therefore the energy projected into the liquid is greater. In addition to making the medium one that will not support breakdown, it is advisable to make the path of rupture as long as possible.

**Measurement of Ultrasonic Power.** The amount of power being impressed on a liquid bath can be measured calorimetrically or electrically by noting the power dissipated in the driving oscillator. Generally, the former method is preferable, since it gives a direct indication of the actual power delivered. The amount of power may also be roughly indicated by the size of the oil jet produced by a transducer when immersed in a bath with its face pointing toward the surface. However, since the waves are almost 100 per cent reflected at the oil-air surface, heat measurements are most accurate. In these, the quartz is set to vibrating and the rise in temperature of the bath measured. The amount of energy needed to give the measured rise in temperature is the actual ultrasonic wattage.

At about 300,000 cycles heating effects become very great. Liquids are heated rapidly, even when iced or externally cooled. The rate of temperature rise may also be extremely rapid. Wood and Loomis showed that the larger the body of liquid the greater the amount of total heat absorbed in it, although the temperature rise may be greater in smaller amounts of material. Solids are also heated intensively at that frequency.

A different method of measuring power was described by Wood.[2] A glass disk about 8 cm in diameter was fastened to a rod by which it could be raised and lowered in a bath. A mound of oil was then excited by ultrasonic means until it reached its maximum height. The glass disk was lowered onto the oil, on which it rested, and was supported by the power of the ultrasonic waves. Weights were then placed on the top of a pan positioned so that its weight was supported by the disk, and additional weights added until the disk sank in the liquid (see Fig. 8-8). The point at which the glass disk sank was an indication of the power output. This apparatus allowed an excellent demonstration of the way ultrasonic waves are built up in a liquid.

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[1] A. von Hippel and R. J. Mower, *Phys. Rev.*, **59**, 820 (1941).

[2] Wood, *op. cit.*

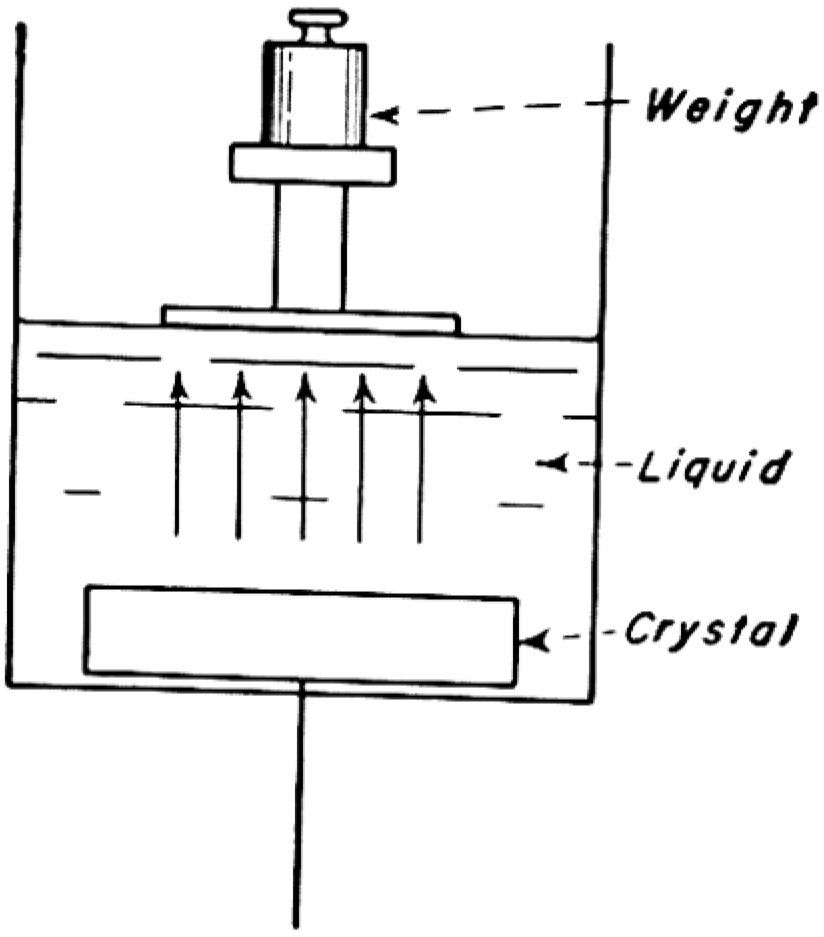


FIG. 8-8. Weight supported by waves.

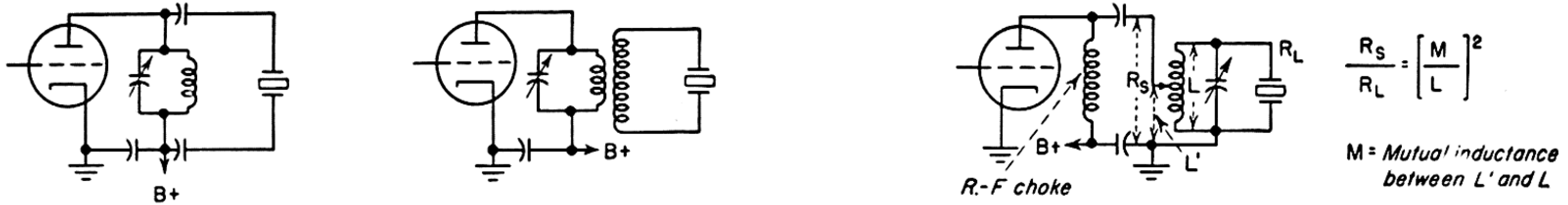
This procedure showed that maximum weight could be supported when the distance traveled by the ultrasonic waves was a multiple of a half wavelength. Under such conditions very great amplitudes of vibration result. The glass disk may be forced down through the ultrasonic waves, but in so doing the resistance encountered seems to take place in steps, concentrated at points of half-wavelength distance.

Wood concluded from this that the way of getting maximum energy into a bath is to adjust the depth in this manner so that the energy builds up by means of standing waves.

Another method of measuring power is by measuring the difference in temperature between the liquid and an outside medium. This can be done by means of a thermocouple. Readings are taken continuously over a time interval. The amount of heat absorbed and hence the power can then be calculated.

In order to keep the temperature of the whole system identical, liquids under test are usually stirred continuously by an electrical stirrer. According to Wood, the increase in temperature may reach a point where it rises a degree every few seconds. Ordinarily, the center of the oil exhibits the greatest amount of heat, and small bubbles of gas form about this point.

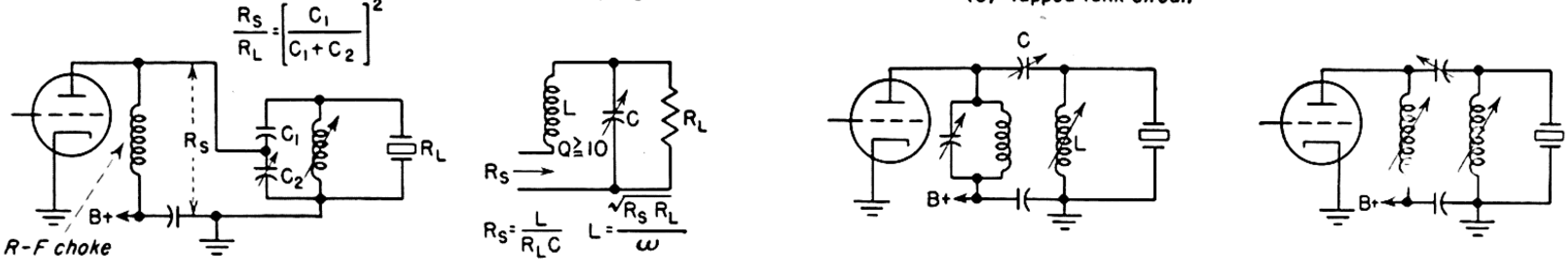
**Coupling to the Crystal.** The coupling of the generator to the crystal is the only critical part of the system and has to be done with care to prevent high-voltage breakdown and also to


B+
B+
$R_S$
$R_L$
L
L'
B+
R.-F choke
$\frac{R_S}{R_L} = \left[\frac{M}{L}\right]^2$
M = Mutual inductance between L' and L

(A) Direct connection

(B) Inductive coupling

(C) Tapped tank circuit


$\frac{R_S}{R_L} = \left[\frac{C_1}{C_1 + C_2}\right]^2$
$R_S$
$C_1$
$C_2$
$R_L$
B+
R-F choke
L
C
$R_L$
$Q \geq 10$
$R_S$
$R_S = \frac{L}{R_L C}$
$L = \frac{\sqrt{R_S R_L}}{\omega}$
C
L
B+
B+

(D) Tapped tank circuit

(E) Impedance transformer

(F) L Matching network

(G) PI Matching network

FIG. 8-9. Methods of coupling output.

provide a maximum transfer of power. The simplest system is merely to connect the crystal across the oscillator output, and such a system works fairly well. Other methods for coupling are shown in Fig. 8-9[1] and are fairly straightforward in their application. These are all designed to give maximum energy transfer from the oscillator to the crystal.

**The Magnetostrictive System.** A typical system utilizing the magnetostrictive principle is indicated in Fig. 8-10. Such systems are useful where lower frequencies are satisfactory. The design of the unit itself is considered elsewhere.

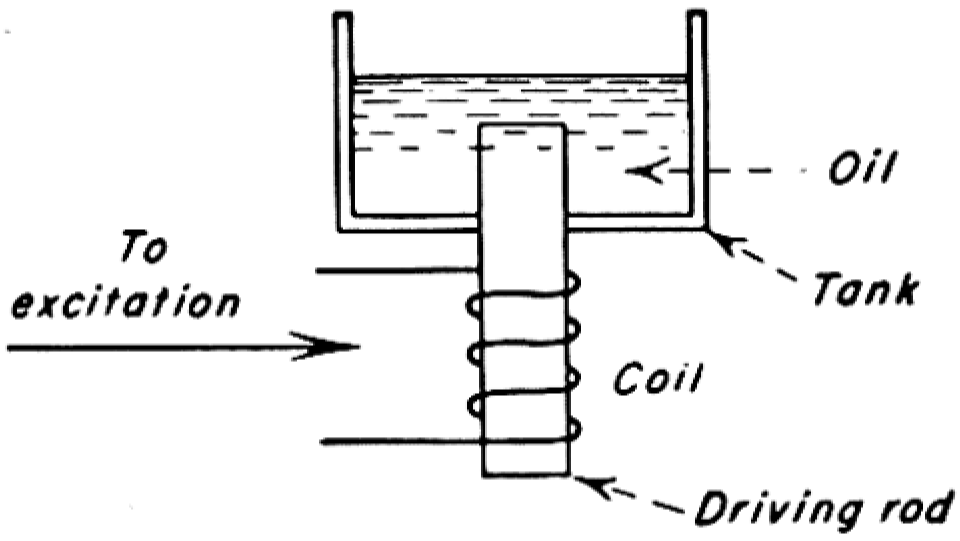


FIG. 8-10. Magnetostrictive agitation system.

Magnetostriction systems can be cooled by a jet of cold water thrown against the vibrating system, and greater outputs obtained in that manner. In some cases the vibrator is directly in the material to be agitated; in others a separate vessel is used in the same manner as with crystals.

These units have the additional advantage that they can be used in gases as well as liquids. Unfortunately the wavelengths obtainable are not entirely satisfactory for all liquid work. A further advantage is that the vibrators can be sterilized for medical or chemical work. They can easily be used in the low audio as well as the ultrasonic range.

**Other Systems.** Agitation can also be carried out by electromagnetic and air-jet generators, but these are rarely if ever used. The electromagnetic type resembles a large radio earphone. Its acoustic impedance is very low, and its action generally unsatisfactory. The unit has some promise in treating gases but is of little use in liquids. The air-jet generator has been rarely used and seems applicable exclusively to the treatment of gases.

**Dispersion and Coagulation.** Most investigations to date have been done in the chemical field, where radical changes can be brought about in many chemicals by using ultrasonic agitation. Both dispersive and coagulative effects occur, and oscillations of frequencies from 20,000 to 100,000 cycles have been used, with oscillators that could produce powers of from 10 to 20 watts/sq cm of ultrasonic energy (maximum).

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[1] Smith and Stumpf, *op. cit.*

One of the more common effects is emulsification, *i.e.*, the mixing of several ordinarily immiscible liquids such as water and benzoil. Several experimenters have investigated such action, and it has been shown[1] that the mixing is strongest at the boundaries of the system, *i.e.*, between the liquid and the walls of the container and also between the liquid and the vibrating system. The greatest effect seems to be due to small particles of one liquid such as water being forcibly propelled into a second one by the vibration. It appears likely that the presence of gases, pressure, etc., also influences the action.

Strangely enough, although strong dispersive actions seem to occur as above, equally strong coagulative effects come about under some conditions. This type of action is more noticeable in the case of aerosols, *i.e.*, systems consisting of small particles of some foreign substance dispersed in a gas. The commonest form such a medium takes is a smoke or mist. The particles may be either solid or liquid. Investigators[2] have experimentally tried the effect of ultrasonics on many such suspensions and have shown that the particles seem to attract each other, become fastened together, and fall to the bottom of the system. It is possible by special methods to photograph the details of this action.

The attractive action depends on various details of the system such as frequency.[3] In other words, there are always optimum frequency conditions for each size of particle in a certain suspension.

Application of such apparatus to the coagulation of dust and smoke is obvious but has never been extensively used.

The formation of emulsions has been described in the following manner:[4] The amount of pressure must be correct, as the action does not occur when it is either too great or too little. When the ultrasonics travels through liquids, it forms compressions and rarefactions that actually disrupt the media. Incidentally, when a liquid is undergoing ultrasonic irradiation, a strong hissing noise should be heard. Many small bubbles are apparently being produced within the liquid and collapsing, producing tremendous pressures. This action was originally pointed out by Lord Rayleigh. It is this production and collapse, sometimes called *cavitation*, which causes the emulsification.

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[1] W. T. Richards, The Chemical Effects of High Frequency Sound Waves, *J. Am. Chem. Soc.*, **51**, 1724 (1929).

[2] C. A. Bjerknes, Remarques historiques sur la théorie du mouvement (etc.), *Compt. rend.*, **84**, 1222 (1867).

[3] O. Brandt, *et. al.*, Zur Theorie der Akustischen Koagulation, *Kolloid Z.*, **77**, 103 (1936).

[4] E. N. Harvey, *Biol. Bull.*, **59**, 306 (1930).

Any strong ultrasonic action is accompanied by violent stirring of the entire material, due to irregularities in the way the material is being agitated.

The presence or absence of gases seems to have a strong influence on what happens. When gas is entirely absent, many actions do not occur, whatever changes appear are unstable, and the chemicals shortly revert to their original state.

**Degassing.** Degassing is the term applied to the expulsion of gases from a liquid or solid. This action is particularly valuable in metals, where inclusions of gas can cause imperfections. Ultrasonic waves can bring about a degassing action.[1] However, the application is influenced by frequency and seems to be better at lower frequencies (about 200 kc).

The degassing appears to be caused by the collection of the gas at the nodes of the waves and by cavitation. The degassing action is not completely understood and is still undergoing further investigation.

**Chemical Effects.** The effects of ultrasonic vibrations upon chemical changes have been thoroughly investigated, and it appears that radical changes may be caused by this means.

Specific reactions will not be discussed at length here. The investigator is referred to the literature for that. However, a brief mention of some of the applications may be apropos.

Increases in quickness of reaction, separation of certain chemicals, crystallization, changes in boiling points, etc., are some of the common effects. Oxidation effects take place more quickly when treated ultrasonically. Especially affected are chemical bonds[2] such as colloidal systems and intermolecular bonds such as the van der Waals type. High polymers can be broken up by ultrasonics, starch changed, etc. Molecule chains may be disintegrated. As already indicated, small particles will gather together in groups when so treated.

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[1] R. W. Boyle, *et. al.*, Cavitation in the Track of an Ultrasonic Beam, *Trans. Roy. Soc. Canada* (111), **23**, 187 (1929).

[2] H. Mark, Some Applications of Ultrasonics in High Polymer Research, *J. Acoust. Soc. Am.*, **16**, 3, 183, January, 1945.

Photographic emulsions rise in sensitivity and resolution when exposed ultrasonically. Color sensitivity becomes greater, and grain size smaller. Under certain conditions, ultrasonics produce light, which may exert an influence on photographic plates.

Other experimentation[1] showed that ultrasonics will vaporize certain volatile liquids and melt wax.

Fogs can easily be formed from many volatile and certain viscous liquids by ultrasonic action. In the case of the volatile ones they are merely placed in a flask in the ultrasonic field. Oils, however, must be treated in a special container, which takes the form of a test tube with its walls drawn close together in the center. This thinner part vibrates particularly vigorously; and if oil is wiped over its outside, it will produce a mist or fog. The oil that remains on the tube forms rings and dots from which the mist exudes.[2] Air currents are also produced around the tube and blow the fog away from it. Exactly why fogs are produced is somewhat questionable, although cavitation may cause them. However, this is not entirely determined as yet.

**Biological Effects.** One of the original effects noted by Langevin during his experiments was the lethal results ultrasonic waves had on small marine life that wandered into the path of his submarine beam. These fish were rapidly killed by the energy, and this action has suggested the use of ultrasonics for so-called "death rays," although these applications have never actually been extensively explored.

Nevertheless, there has been much experiment on the biological effects of ultrasonics, particularly on the effects produced by very strong ultrasonic fields on small life, such as various frogs, animals, and fish. Certain of these small animals may be either killed or damaged by the rays, and similar effects occur when experimenting with different types of cells, protozoa, and blood corpuscles. The particles of matter are actually torn to pieces. Rapid and radical changes in body temperatures are also produced.[1] These effects seem to be caused by the formation of bubbles of gas within the body and by cavitation.

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[1] F. L. Hopwood, Experiments with High Frequency Sound Waves, *J. Sci. Instruments*, **6**, 34 (1929).

[2] Wood and Loomis, *op. cit.*

The heart action of animals may be changed by ultrasonics.[2] Artificial fever may be produced by the waves, and they have also been suggested for diathermy and knifeless surgery.

A list of other common biological phenomena follows: changes in seed-germination time, destruction of reproductive ability of cells, disintegration of bacteria to release enzymes, etc., separation of antibodies, changes made in the character of milk, changes in albumin, etc.

The application of such a generator to one problem has been discussed.[3] The bacteria is placed in a solution and supported in the ultrasonic field, *i.e.*, immersed in a bath through which strong ultrasonic energy is being transmitted. A point is picked where the field is strongest as indicated by the maximum amount of surface agitation in the flask. The sample is then exposed for some time, after which it is ready for further analysis.

**Metallurgical Applications.** One of the chief metallurgical applications is that of dispersion, *i.e.*, mixing small particles of metal throughout some sort of solution, *e.g.*, copper and water. This has been successfully done with many common metals. Very fine particles with a diameter of a few microcentimeters may sometimes be obtained. Frequencies of about 400 kc were used.

As already mentioned, the passage of ultrasonics through a liquid may be indicated by means of small particles that orient themselves in the beam. In a like manner, any suspended particles will orient themselves, particularly if of rodlike or similar shape.[4]

These experiments were carried out with metals merely placed in a solution. Further work[5] was done while depositing metals electrolytically, and much finer and more highly dispersed deposits of metal were accomplished. Work was done by the same investigator on photographic plates, and he claimed superior resolution, etc.

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[1] *Ibid.*

[2] Forster and Holste, Zur Biologischen Wirkung von Ultraschall; *Naturwissenschaften*, **25**, 11 (1937).

[3] F. W. Smith and P. K. Stumpf, Ultrasonic Generators, *Electronics*, April, 1946.

[4] N. Marinesco, Préparation des colloides par dispersion ultrasonique, *Compt. rend.*, **196**, 346 (1933).

[5] B. Claus, *Z. tech. Physik.*, **15**, 74 (1934).

Other work was as follows:

Sokolov found that melted metals when ultrasonically treated solidified more quickly and were of finer grain.

Metals that would usually not mix can be kept mixed by ultrasonics while solidifying.

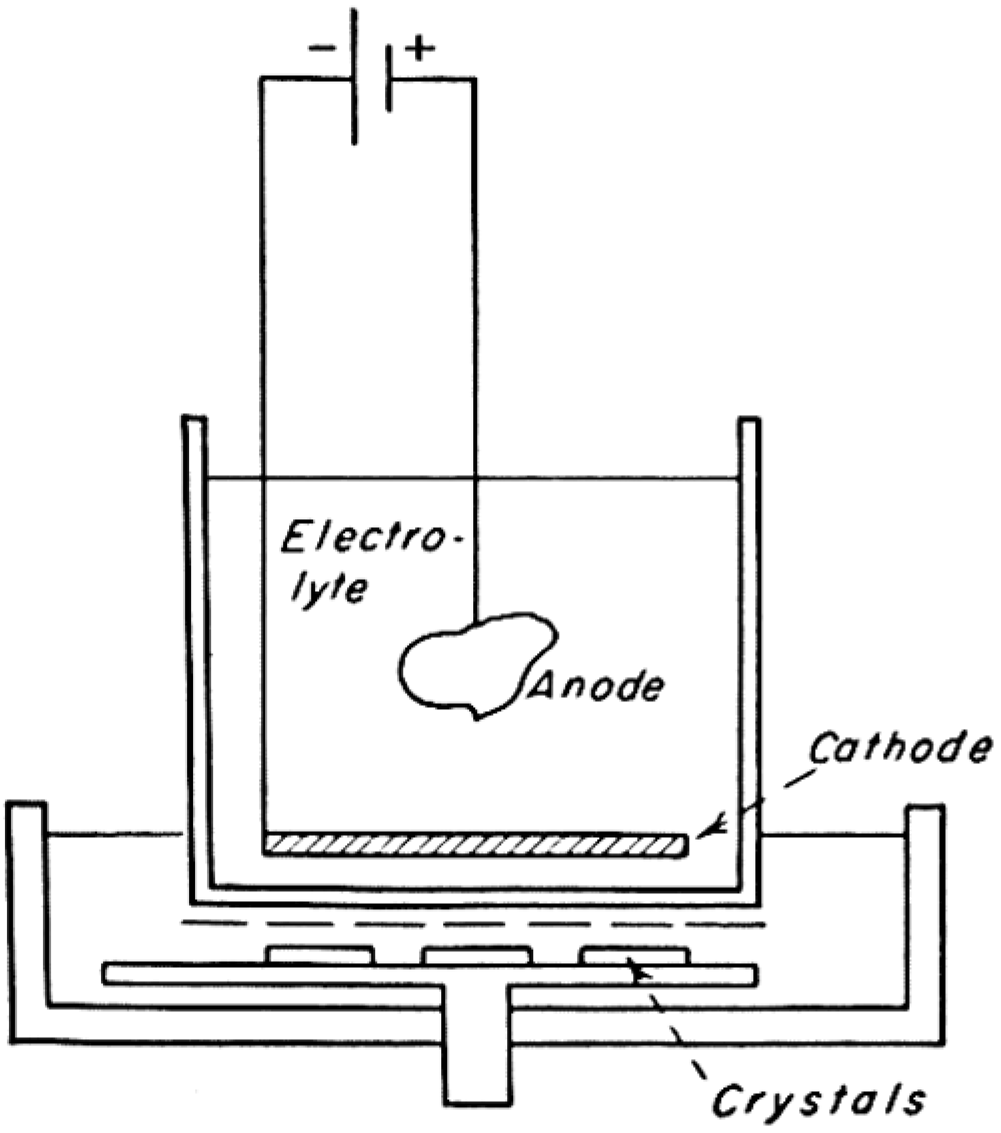

FIG. 8-11. Apparatus for electrolytic dispersion.

The magnetic properties of nickel are changed (using a frequency of about 20 kc).[1]

Alloys and metals in which nitriding takes place have their structure improved and the process speeded up.[2]

The metallic action was described by Richards[3] in the following manner. This is applied to metals in a liquid state. The walls of the container have strong *S* waves set up in them, which fling drops of water into the metal. These drops each become covered with a thin film of metal, which breaks and throws minute particles of metal into the water.

Most solid bodies such as metals, which exhibit considerable adhesion between the parts, are not easily broken down by ultrasonic action. Some slight breakdown may be sometimes noticed in those solids which have poor cohesion, but generally this phenomenon is not efficient enough to be useful. The possible extension of the field of ultrasonics in this direction must await the design of generators of much greater power capabilities.

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[1] G. Schmid and U. Jetter, Influence of Longitudinal High Frequency (Supersonic) Vibrations on the Magnetic Behavior of Nickel, *Z. Electrochem.*, **47,** 155 (1940).

[2] G. Mahoux, Influence of High Frequency Oscillations upon the Treatment of Metallurgical Products, *Compt. rend.*, **191,** 1328-1332 (1930).

[3] W. T. Richards, *J. Am. Chem. Soc.*, **51,** 1724 (1929).

The arrangement for electrolyte dispersion (after Claus) is shown in Fig. 8-11.

**Effects on Gases.** Gas effects have already been discussed in connection with aerosols. The best and commonest example is the well-known Kundt dust figures, which represent a coagulating effect of the ultrasonics in a gas.

The reason for this action seems to be that the particles do not all travel the same paths because of their different sizes and because of characteristics of the system (such as frequency). Studies of this action may be found in the literature.[1] Magnetostriction generators are commonly preferred in gas work, and frequencies of 15,000 to 30,000 cycles are common.

A setup for investigating the behavior of ultrasonics on gases is shown in Fig. 8-12. A crystal unit may be used. The window is used for observation. By the use of this apparatus photographs of the action of aerosols can be taken.

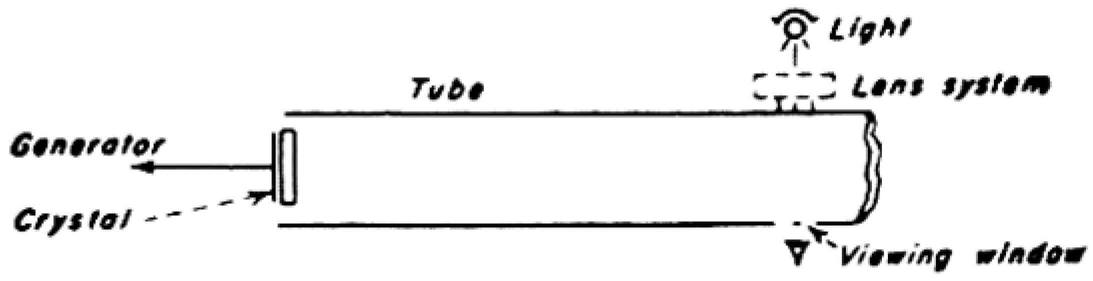

FIG. 8-12. System for investigation of ultrasonics in gases.

It is possible that some of the effects described are not entirely due to the ultrasonic vibration but are at least partly caused by the heat generated by the passage of the waves. Considerable rises in temperature may be observed in a liquid through which ultrasonics are traveling due to their absorption in the medium. For this reason, it is sometimes difficult to determine whether a particular effect is caused by the ultrasonic vibrations or by the heat associated with them.

A number of experiments were performed by various investigators to show the presence of heat. None of these are particularly important. The effect is probably most simply shown[1] by holding a thermometer manually in a solution under agitation. In doing so, the friction between the thermometer and the fingers will generate sufficient heat to make the thermometer too hot to handle.

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[1] O. Brandt and H. Freund, *Z. Physik.*, **92,** 385 (1934)

Little practical application of the heat effect has been found to date. However, the use of such generators for diathermy has been suggested in Germany.

When small particles or objects are placed in a bath, greater heating takes place at the boundaries; this is also true for an object that has boundaries, *i.e.*, inclusions, within it, and such objects will become heated much more rapidly than clear ones.

The heating effect makes it necessary to watch closely and sometimes control the temperature of a system under investigation in order to see that the heat itself does not cause reactions (or, sometimes, prevent them).

It may be emphasized that the agitation field, though a sensational one in certain aspects, has never been extensively explored and awaits more work. It appears to offer great potentialities for the future. However, most of the experimentation done to date is inconclusive from an engineering point of view.

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[1] Wood and Loomis, *op. cit.*

# CHAPTER IX

# MAGNETOSTRICTION

The discovery of the magnetostrictive effect is usually credited to Joule.[1] However, the effect that bears his name, though one of the most famous and also the one of which the greatest number of applications have been made, is far from the only magnetostrictive effect. To explain certain results that occur in practice, it is desirable to discuss the entire phenomenon more completely.

The most general statement of magnetostriction may be made in the following manner. When a material is in a particular magnetic state, apparently only one combination of physical or chemical characteristics can exist within it. In a like manner, once the particular chemical or physical characteristics of a material have been determined, the magnetic state has also been defined. The progress of magnetostriction in its most general sense is therefore the definition of a set of physical characteristics by controlling the magnetic ones, and vice versa.

There are many possible physical changes a material may undergo; and as might be expected, a large number of magnetostriction effects are accordingly mentioned in the literature. Those mechanical changes due to a change in the magnetic field are referred to as *direct effects*. They may be in the linear dimensions, in the circular ones, or in the volume. The Joule and the inverse Joule effects are among the first of these. Both of these are changes in the length of a rod or bar due to the magnetic field.

Other linear effects are the Guillemin, a bending of the rod caused by the field, and a change in Young's modulus. Any of these reactions may theoretically occur separately, or they may all occur simultaneously. In practice, the effects are more likely to occur as a combination of several than alone. The Joule is the most famous of the direct effects and is the most extensively considered in this context for that reason.

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[1] J. P. Joule, *Phil. Mag.*, **30,** 46 (1847).

The circular changes take the form of a twisting, which is referred to as the *Wiedemann effect*, and of a change in the coefficient of rigidity. The former is rather well established in the experimental laboratory, but the exact order of the latter is still subject to question.

A change in volume with the field is known as the *Barrett effect*. It also appears likely that a change in the bulk modulus takes place, although this, too, is somewhat questionable.

All these direct effects are physical changes caused by the action of the magnetic field. Most of them are extremely slight and are therefore not considered at all in ordinary work with magnetostriction units. Special methods must actually be resorted to in order to investigate even the best known and largest, *i.e.*, the Joule effect. A brief mention of such apparatus may therefore be of interest.

However, before attempting to observe the Joule effect, certain precautions must be taken. The samples must be carefully magnetized in such a way that they are kept free of extraneous fields. The magnetic fields must be very uniform, and the sample placed in them symmetrically. The temperature must be exactly controlled, and the part supported in such a manner that the effect is not physically interfered with in any way.

The apparatus used in the theoretical laboratory for the investigation of this effect is known as an *extensometer*. It consists of a set of rods connected so that the total movement at one end is much greater than the activating motion applied at the other.

The most commonly used arrangement is a modification or variation of the Michelson interferometer used for the investigation of light. By means of this apparatus, a mirror fastened to the end of the extensometer bar is made to shift the interference fringes that the instrument projects on a screen. The change must then be interpreted in terms of the change in length of the magnetostriction bar. The unit is extremely sensitive, and the minute changes in dimensions associated with the Joule effect may accordingly be easily examined with it.

The statement seems to have been originally made by Le Chatelier that once a body of material was placed in a state of chemical and physical equilibrium, it would resist any attempt on the part of an outside agency to change that equilibrium. This statement may be taken as the reason for the inverse magnetostriction effects.

The inverse effects may be subdivided in the same manner as the direct ones. The most well known, because they are the most easily investigated, are the Villari and the transverse Villari, both of which are linear. These may be examined by applying the proper linear mechanical forces to a bar in which they can occur and using any of the known ways of investigation of its magnetic properties during this application.

The circular effects are known as the *second Wiedemann*, which is a change in the longitudinal component of magnetism due to a twisting of the rod, and the *Wertheim*, which bears a close resemblance to the Wiedemann except that the sample is initially a longitudinally magnetized bar.

The changes in volume are known as the *Nagaoka-Honda effect* after the men who did extensive work in the field in Japan.[1] This is usually demonstrated in the form of a change in the magnetic induction caused by hydrostatic pressure.

**Miscellaneous Effects.** Besides the listed actions, which can be classified in a more or less regular manner, there are a number of other effects that have been often observed but never entirely satisfactorily explained.

Among these are a change in the material resistivity, a change in the thermoelectromotive force, a change in the frequency of a vibrating body, and the production of the so-called "magnetic ticks" or clicks that occur when a body is undergoing magnetization.

The Joule and Villari effects are the only ones of any interest in design work of longitudinal oscillating bars, which are by far the most commonly used. However, other effects may in time be more extensively applied as more and more is known about them.

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[1] H. Nagaoka, "On Magnetostriction," International Electrical Congress, 1904.

**General.** The magnetostriction effect has been widely investigated by Pierce[1] and his students, who first applied it to many practical problems and conceived of the idea of using it to control and maintain oscillations in a bar of metal, which is then used as a device to control the frequency of electronic oscillators, as a filter, as a time standard, and for the production of ultrasonic vibrations in various media. In short, the effect may be applied to many uses just as the piezoelectric effect may.

Magnetostriction units have also been used as the driving elements in agitation systems and have been proposed for the resonance testing of materials. They have not been extensively used in testing materials by other methods. Moreover, the use of magnetostriction as the basis for ultrasonic signaling systems is widespread, especially in the lower frequencies and in applications such as submarine signaling, where considerable amounts of power are necessary. In such systems one magnetostriction rod can be used in an oscillator and form the transmitting transducer, while another rod is attached to a receiver and indicator and acts to transform the ultrasonic signals to electrical ones.

The output of the average magnetostriction unit is much less than a crystal when both are being used to receive mechanical oscillations and transform them into electrical signals. As a matter of fact, the ratio of output is approximately of the order of $1 \times 10^{-2}$, although it varies for individual designs and applications. As a transmitter, the magnetostriction rod is also less efficient than the crystal but has the great advantage that almost any amount of driving power can be applied to it.

**Controlling Device for Oscillators.** As already indicated, the magnetostriction bar may perform the same function as a crystal in stabilizing the frequency of an oscillator, and in such use it maintains the frequency with a constancy that compares favorably with the latter.

The action is based upon the fact that the coil and rod act as a variable inductance fluctuating in such a manner that it opposes any change in the oscillator frequency and moreover changes very sharply for only a minor variation in the frequency.

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[1] G. W. Pierce, Magnetostriction Oscillator, *Proc. Am. Acad. Arts Sci.*, **63**, No. 1, April, 1928.

The range of voltage, etc., over which such units act suitably is wide and also compares favorably with that in crystal work.

**Materials.** The ordinary metals used in the production and reception of ultrasonic waves are the alloys of nickel, chromium, iron, and cobalt. Others are Invar, stoic metal (36 per cent nickel and 64 per cent iron), and Monel (68 per cent nickel, 28 per cent copper, and small amounts of other metals). The most common are nickel and permalloy (45 per cent nickel, 55 per cent iron). These last two materials produce magnetostriction effects that are mutually reversed; *i.e.*, in a particular polarity of field one material will shorten while the other will lengthen. However, the total absolute dimensional change is about the same.

It has been experimentally discovered that annealing adds to the magnetostrictive properties of such bars, of whatever metal they are made.

The only materials that show regular behavior characteristics as regards the amount of change in length caused by a particular magnetic field strength are rods of nickel and annealed cobalt. Almost all other materials will exhibit these regular length variations until the field becomes stronger than a limiting value, at which point the length change exhibits a change in sign, *i.e.*, goes in the opposite direction.

Combinations of materials may also be used for vibrating bars. For example, tubes of nickel can be made hollow and filled with lead or type metal to bring down the velocity of wave propagation and thus produce very low-frequency waves. Again, materials of different temperature coefficients can be combined to get a desired characteristic. Thus, one material with a negative temperature coefficient may form one part of a bar, while a piece with a positive coefficient may form the other part. In this way the temperature coefficients balance out and the bar is more stable to temperature changes. These bars may be either longitudinally composite or concentrically composite, depending on how they are joined.

In simple materials the magnetostriction effect decreases as the temperature rises and vanishes at the Curie point.

When a steady field is applied to the bar in this manner, the change in length is minute; *e.g.*, in nickel it is about $1 \times 10^{-6} L$ per gauss. However, when the field is oscillating, the effect is much greater, since the elastic forces of the bar no longer oppose the changes in length and the only force that must be overcome is the viscosity of the material.

The change in length in the bar due to the magnetostrictive effect will usually be very small unless the vibrating frequency is resonant at the length of the bar, in which case the greatest change will be about $10^{-4} L$, where $L$ is the length of the bar. The change under nonresonant conditions is about 25 parts in a million. It may be either positive or negative depending on the material and the temperature. However, the force associated with the small change in length is the entire elastic force of the bar, and as a result large ratios of force to applied current are common. When the bar is resonant, this change becomes greater. If the flux intensity is low, the change in length is proportional to its square. Ordinarily polarizing units must be used with magnetostriction bars.

In a solid part there is usually some loss due to eddy currents, which flow in the material. Because of this, magnetostriction oscillators are usually constructed of thin tubes or fine wires, fastened together to form a single solid part. There are also losses due to hysteresis. The use of laminations cuts down these losses and provides fairly wide-band elements.

The mechanical impedance of the system tends to be large, and magnetostriction driving systems can therefore be used to drive high-impedance systems, such as solids and liquids, but are not efficient for generating sound in air.

Nickel, which is most often used for ultrasonic work, is not completely satisfactory for stabilizing frequency, since it does not maintain so consistent a frequency as other materials.

**Systems.** *The Magnetostriction Oscillator: The Rod.* If a rod is magnetized and a coil wrapped around it and the rod is lengthened or shortened by compression or tension, voltage will be induced in the surrounding coil (Fig. 9-1). When the rod is allowed to return to its original position, another voltage will be induced but of opposite polarity. If then the rod is vibrated continuously at some a-c frequency, it is obvious that an a-c voltage of the same frequency will be induced in the coil, and the magnitude of that voltage will be proportional to the amplitude of vibration. This roughly describes the action of a magnetostriction receiver when sound waves strike it. At some particular frequency the rod will resonate, and therefore maximum voltage will be induced. However, the tuning may be fairly broad, and the receiver will respond to a wide range of frequencies.

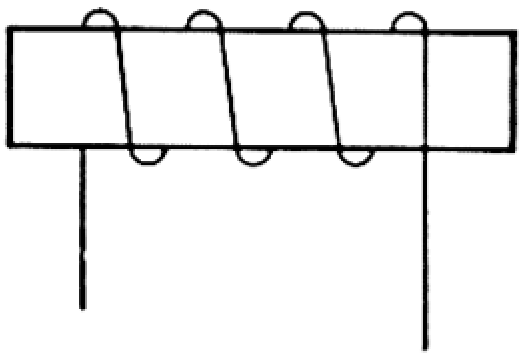
FIG. 9-1. Magnetostriction rod.

In a similar manner the reverse effect will take place; *i.e.*, a voltage may be impressed upon the coil of wire, and the rod will then vibrate at the frequency of the applied voltage and with an amplitude roughly proportional to the voltage magnitude. If this is done, ultrasonic waves will be radiated from the ends of the rod. At the resonant frequency the effect will be greatest and waves of the greatest amplitude will therefore be produced.

In both cases, if the rod is supported in the center, as on a knife edge, it will have a secondary resonance point at every odd multiple of the fundamental.

If the rod were totally magnetized, every time a flux were set up it would shorten, without regard to the flux direction. The rod will therefore vibrate at twice the frequency of the exciting a-c voltage. It is more usual to work with magnetized rods, and therefore some means is normally included for maintaining the magnetization. This may be a superimposed constant current, or a permanent magnet may be used (Fig. 9-2).

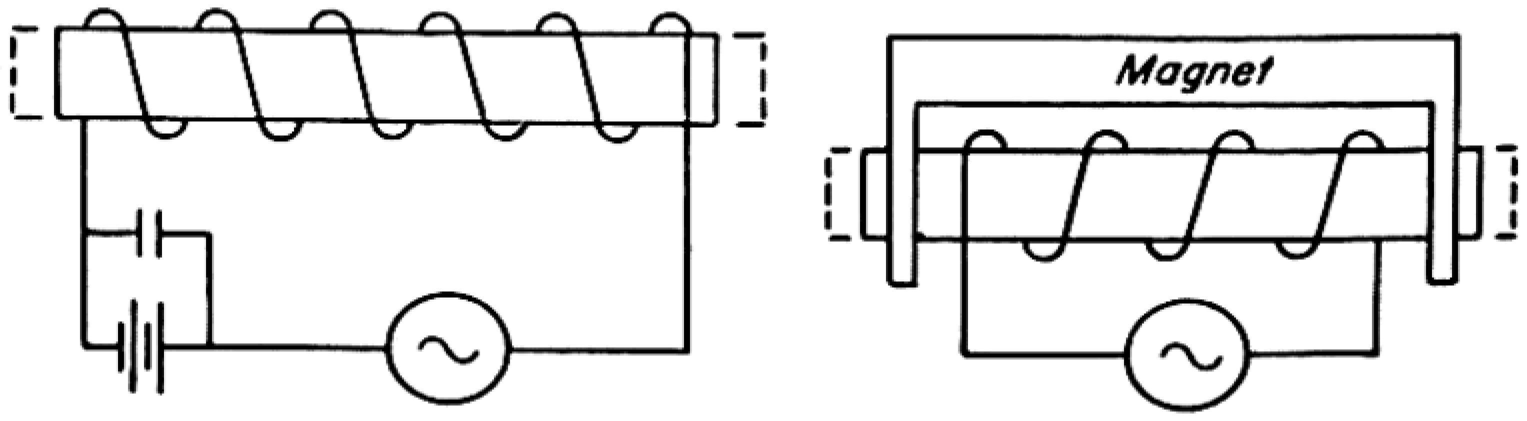

FIG. 9-2. Methods of magnetizing the rod.

When a material does not retain magnetism efficiently, a small permanent magnet may be placed somewhere in the vicinity, within 6 in. or so of the bar, and will maintain its polarity by induction.

Because the bar is polarized when it is magnetized in any such manner, it will vibrate at the same frequency as the frequency of excitation.

*Dimensions and Frequency.* In any ordinary case the magnetostriction rod is designed to oscillate at its fundamental mode, although in some cases harmonic modes may also be used. These modes are almost always longitudinal. The critical dimension accordingly is the length. Harmonic modes are used only in those cases where it is impossible to get the required frequency by means of the fundamental ones. Torsional modes are practically the only other ones used besides the longitudinal.

The theoretical formula for the velocity of ultrasonics in such a longitudinal bar is

$$c = \sqrt{\frac{\text{Young's modulus}}{\text{density}}}$$

It may be noted that this is not the formula given for velocity in a bulk medium, but it is rather what is sometimes referred to as the velocity of the compressional type of wave, or as bar velocity, because it exists only in a medium where the ultrasonic energy extends to the limits of the part through which it is traveling in a direction parallel to the main motion. Accordingly, the effect of the sides of the part must be taken into consideration when the velocity is being computed. The waves in the magnetostriction bar are ordinarily of this type because of the small cross-sectional area of the bar.

The ordinary fundamental bar would be one-half the wavelength. The length of the bar can accordingly be calculated when the velocity or wavelength in a particular material is known and would be

$$L = \frac{K}{2f}\sqrt{\frac{E}{\rho}}$$

where $K$ = order of harmonic
$L$ = length
$E$ and $\rho$ = modulus of elasticity and the density, respectively

Using this formula, it can be seen that at about 20,000 cycles, which may be considered as the boundary point between sonic and ultrasonic waves, a nickel bar would be about 5 in. long. Since the bar becomes shorter as the frequency becomes higher, this is the very longest that it is likely to be.

Naturally, the length would change with the materials used and vary in each one according to the frequency desired and the velocity of the ultrasonics in the rod. For example, in Nichrome, where the velocity is about $1.96 \times 10^5$ in.,

$$L = \frac{1.96 \times 10^5}{2f}$$

where $L$ is the length. The cross-sectional dimensions of a bar of this nature would vary from ⅛ to about ¼ in. in diameter.

Incidentally, one of the advantages of the magnetostriction bar is that it can be made with a smaller cross-sectional area than the quartz crystal and can therefore be inserted into ultrasonic fields where the interference produced by a transducer of a larger cross section would destroy the action under investigation.

The ordinary range of magnetostriction bars is from 5,000 to about 60,000 cycles. After that point, the rods become so short that they cannot be conveniently handled.

The magnetostriction rod is almost the only device used for the production of ultrasonics or the stabilization of oscillators under a frequency of about 25,000 cycles. It has been used in laboratories to produce oscillations up to a maximum of about 2 mc, but at the higher frequencies its output is so small as to be negligible. At the present time, the maximum usable frequency is about 60,000 cycles, where a bar about 1½ in. long may be used. Such bars can be designed from the nomograph (Fig. 9-3).[1]

*Shape.* Magnetostriction bars have been made in many types and shapes. These variations have been dictated by two main considerations: the elimination of losses in the bar and the desire to control the shape or field pattern of the transmitted beam. When a long rod or bar of the type so far discussed is excited so that it sends out ultrasonic vibrations, those beams

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[1] R. C. Coile, Magnetostriction Resonant Frequencies, *Electronics*, September, 1947.

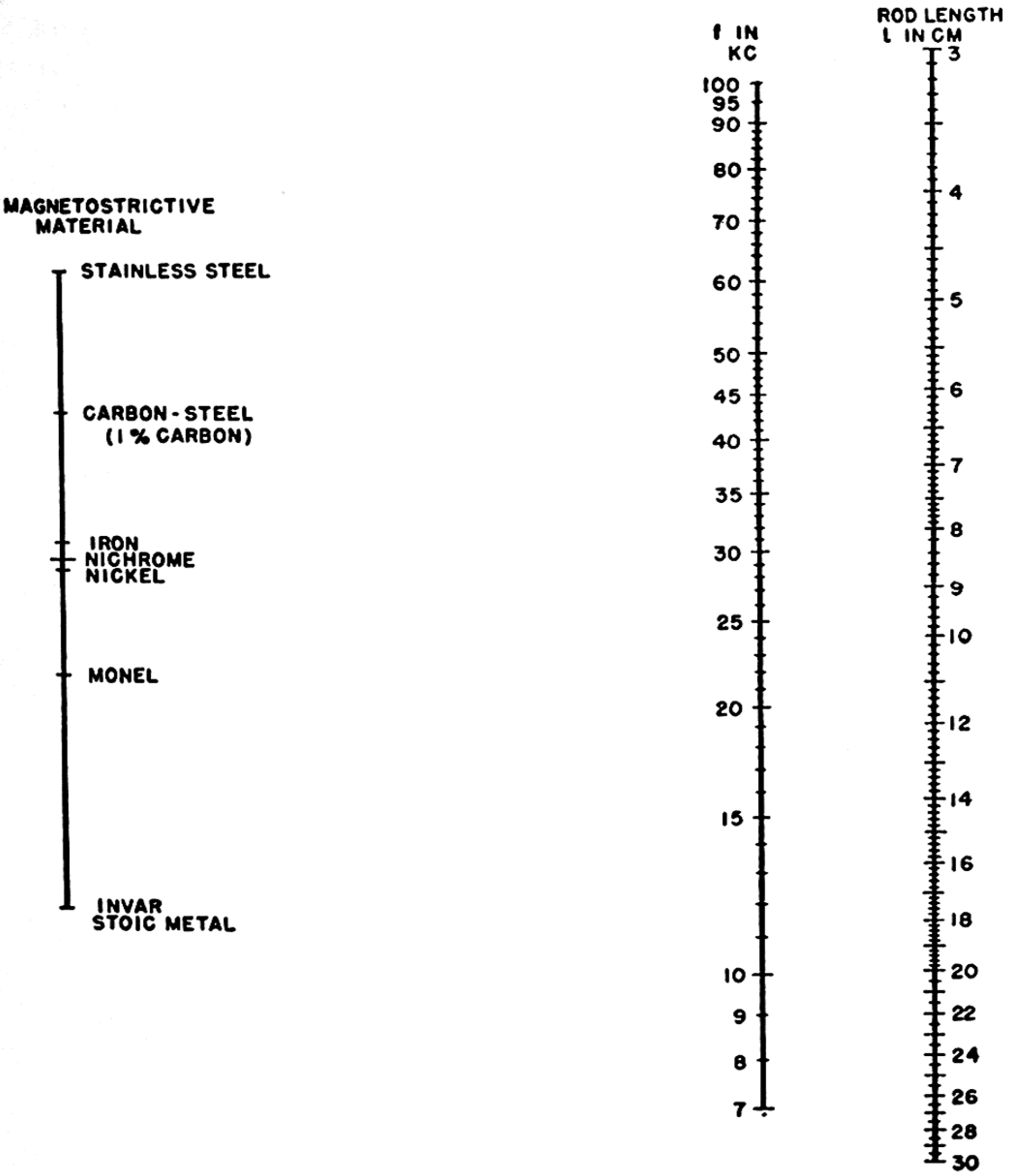

FIG. 9-3. Magnetostriction bar design nomograph.

are transmitted out from its ends only. The pattern of such a beam may be seen from Fig. 9-4.

In order to control the shape of the beam, some transducers have been designed that are highly directional. Others are so proportioned that they produce a beam that spreads out evenly in all directions. To accomplish this latter objective, circular rings may be set into oscillation in such a way that the radius of the ring is continually changing with the excitation (Fig. 9-5). In this case the ultrasonic energy will spread out evenly from the center of the ring in the same manner that light spreads out from a point source. Special ring transducers were constructed by Marconi, in which the magnetostriction rod, which was nickel, was fixed and the windings were allowed to move.

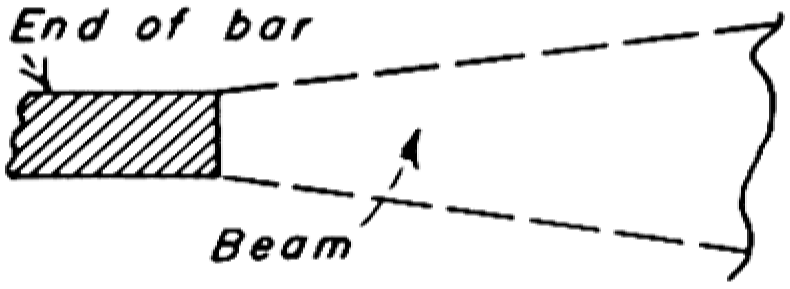

FIG. 9-4. Beam from end of bar.

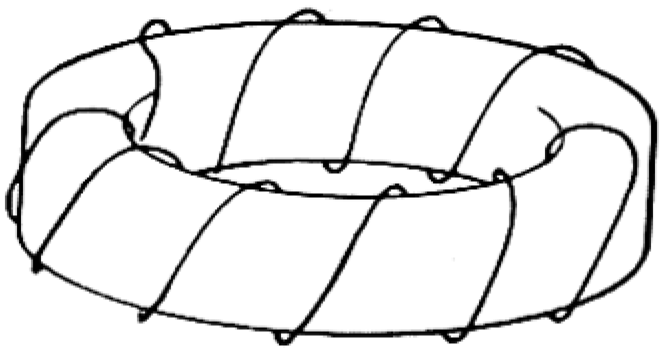

FIG. 9-5. Simple ring oscillator.

If the outside edge of such a ring is serrated or has teeth attached to it, the frequency of oscillation will be lowered. This is one way of attaining higher frequencies than would otherwise be possible.

The frequency of such a ring is

$$f = \frac{c}{2\pi r} \sqrt{1 + (1 - K^2)}$$

where $K$ is the order of harmonic and the letters have the usual meanings. Magnetostriction units can also be formed of a number of rods fastened at one end to a large mass from which they point radially outward, so that the ultrasonic waves are sent out from their free ends.[1] Each spoke is then separately excited longitudinally. However, each rod has a separate winding, and those windings are so arranged that the flux in each one is of the opposite sign from that of either of its neighbors. This is done so that there will be a closed magnetic circuit.

For high frequencies other special rods have been suggested. These may be very short cylinders or types such as beaded rods, (Fig. 9-6).[2] These are bars which have grooves cut in them to raise the frequency. The production of higher frequency oscillations is particularly important, since frequency is one of the main limitations to the use of magnetostriction.

[1] W. Kallmeyer, German Patent 607,048, 1934.

[2] G. W. Pierce, U.S. Patent 1,882,397, 1932.

All these units are usually constructed of some form of laminated material in order to cut down losses from eddy currents. Either they may be of strip construction, or rolled sheets or stamped rings may be used depending upon the size and type of unit.

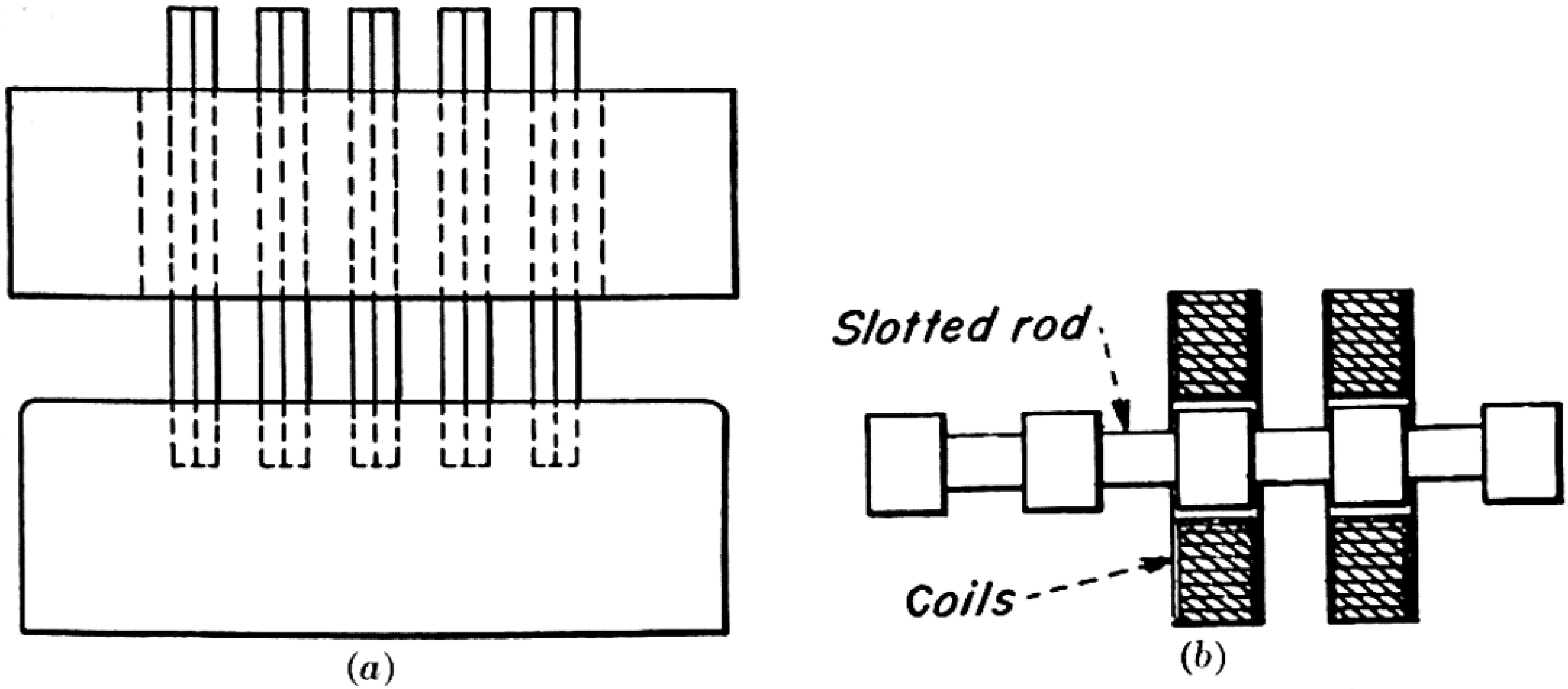

FIG. 9-6. High-frequency rods: (a) cylinders, (b) beaded rods.

The magnetostriction rod may also take the form of a tube, usually of metal, inside which the coil is placed, instead of being wrapped around it. This is of interest in those cases where the unit is to be submerged in order to keep it waterproof, or in those instances where a very large cluster of transducers are to be operated side by side and space is a consideration.[1]

Rods have also been constructed in small vacuum chambers so that they are less affected by their surroundings.[2]

Movable weights have been used to change the frequency of oscillation, giving a sort of tunable rod. Still another design used with agitating systems is the combination of the rod and the cup in which the material is placed for exposure to the ultrasonic energy. The rod is firmly fastened to or integral with the base of the cup, so that it is vibrated directly. The unit may be cooled by a water jacket or by a jet of water directed against it at a convenient point. It will operate over any range from the middle audio up to the low ultrasonic. This rod would normally be from 5 to 10 in. long and about ½ in. in diameter.

When placed in a bath or other medium where there is danger of stray pickup, all ultrasonic units must be suitably shielded to eliminate extraneous signals. This can be done by placing the entire unit in some form of holder or placing a braided shield about it. Naturally, this shield must not interfere with the ultrasonic beam.

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[1] G. W. Pierce, U.S. Patent 2,063,949, 1936.

[2] G. W. Pierce, U.S. Patent 1,882,394, 1932.

When simple rods are cut to a given frequency, first the frequency is calculated from one of the formulas already given, and the rod cut slightly oversize. It is then tried out in an actual oscillator and ground down to calibrate with an exact standard, which may take the form of another bar. Calibration may also be made against any exact source of frequency by beating the magnetostriction oscillator with it. Exact frequency is only rarely required, and on other occasions the bars may merely be cut to size and will be exact enough for ordinary use.

Many bar designs have been used in specialized apparatus over a period of time and are recorded in the literature.

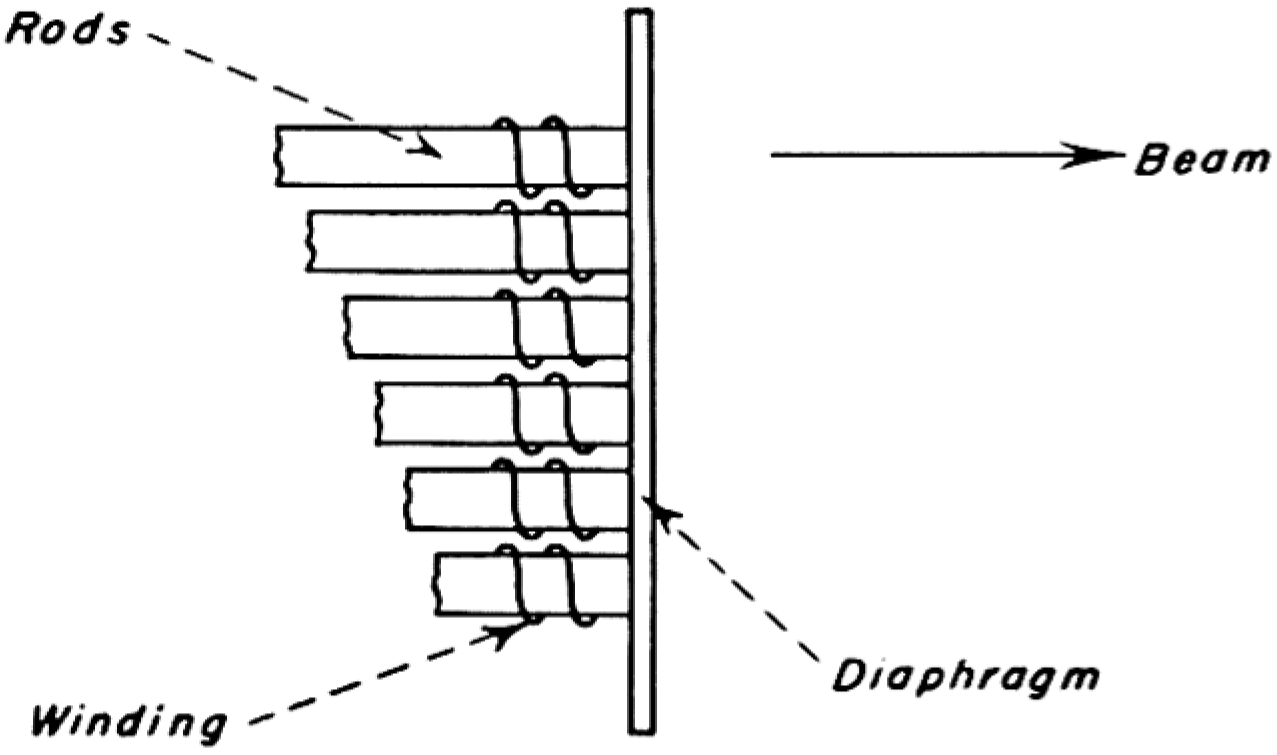

FIG. 9-7. Rods and diaphragm.

*Diaphragms.* The ends of the rods, whatever shape they may be, are usually coupled into a diaphragm (Fig. 9-7) that actually acts to send the ultrasonic waves into the medium. When the diaphragm takes the form of a large sheet, driven by one or more rods, one of the problems is the tendency of the plate to vibrate with some sections out of phase with the other ones. To overcome this the diaphragm can be broken up and a number of smaller diaphragms used, each so connected that it is in phase with the others. An alternate method is to place the vibrating rods so that the entire face of the diaphragm is in phase.

The use of a plurality of rods driving a single diaphragm seems to have originally been due to Pierce. In this case all the rods must have approximately the same period. One end of the core is attached to the diaphragm (Fig. 9-8).[1] The activating coils may be either in series or parallel. The units have greater power capabilities than single units of the same size and have less eddy current and other losses. The complete system from the patent is disclosed in Fig. 9-9.

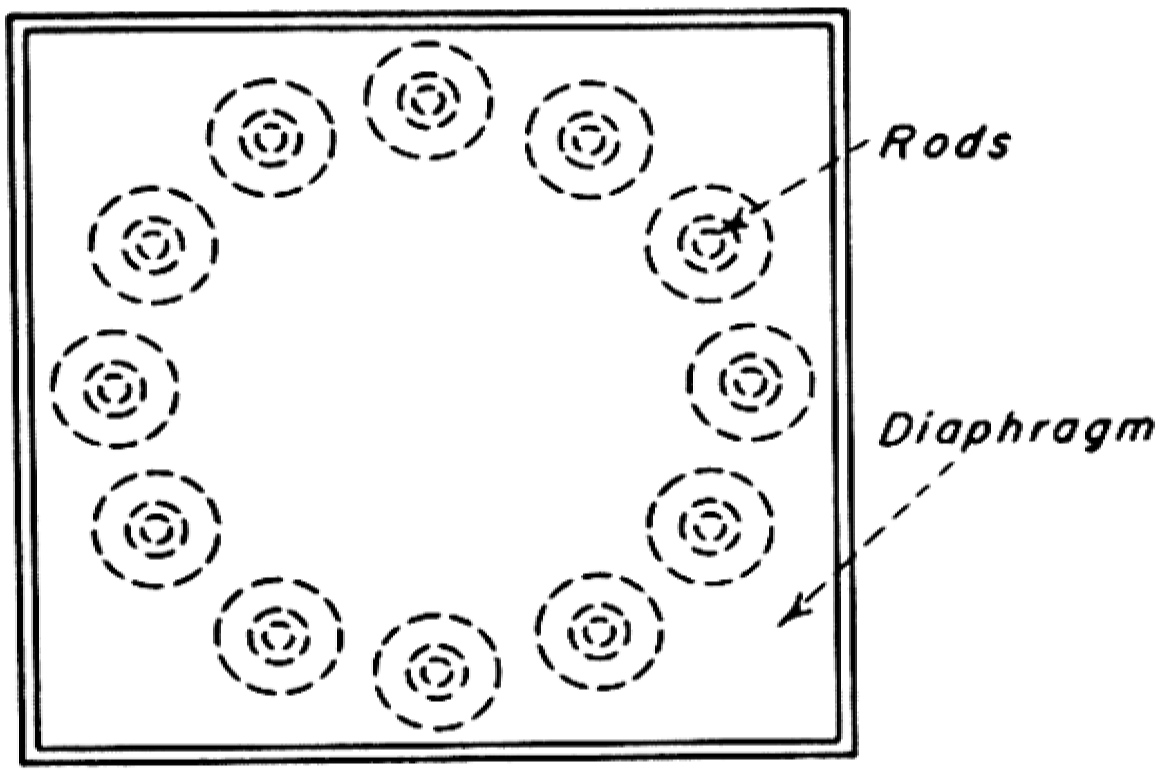

FIG. 9-8. Connection of rods.

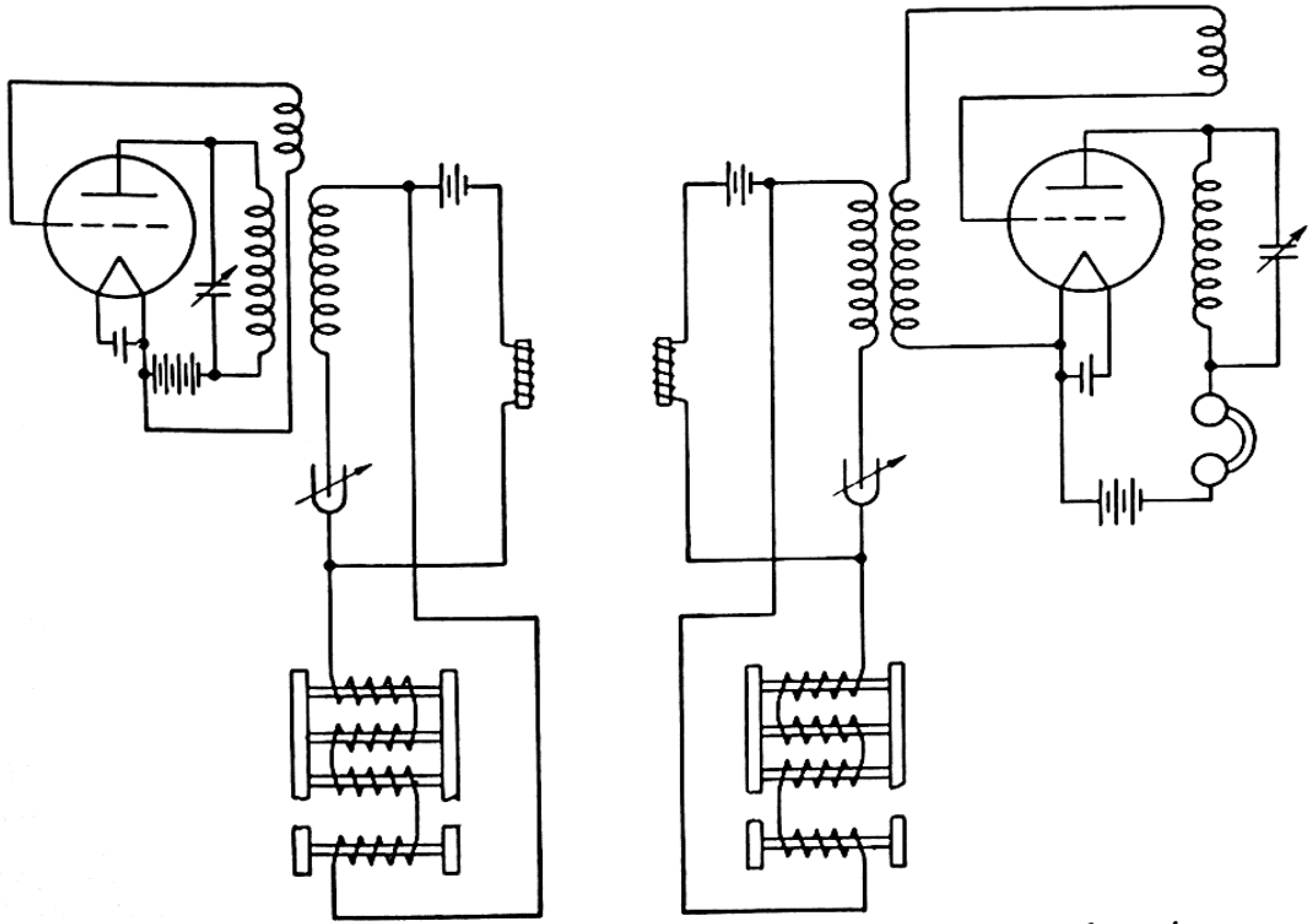

FIG. 9-9. Magnetostriction diaphragms in transmitters and receivers.

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[1] U.S. Patent 2,014,411, 1935.

A more complicated modern device of the same sort is illustrated in Fig. 9-10.[1] The transducer consists of 600 nickel tubes inserted in coils which are connected in series-parallel. A diaphragm 16 in. in diameter and about 1 in. thick is fastened to

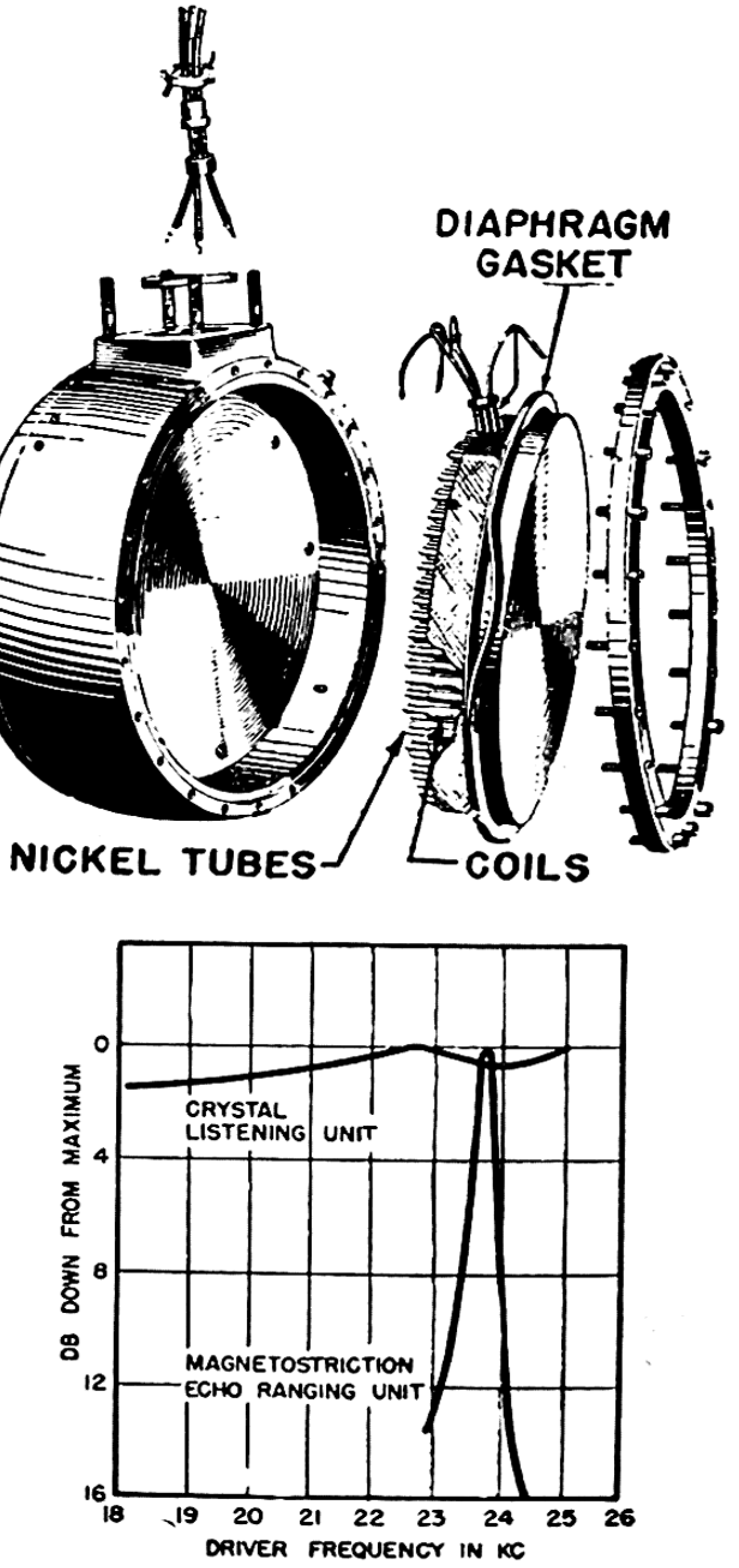

FIG. 9-10. Modern rod and diaphragm transducer.

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[1] R. J. Evans, Echo Ranging Sonar, *Electronics*, August, 1946.

one end of these rods. The diaphragm is made of steel. The rods are polarized by direct current. The length of the steel-diaphragm–nickel rod is a half wavelength, for resonance. The frequency response is also indicated.

The method of mounting the unit on a ship is shown in Fig. 9-11.

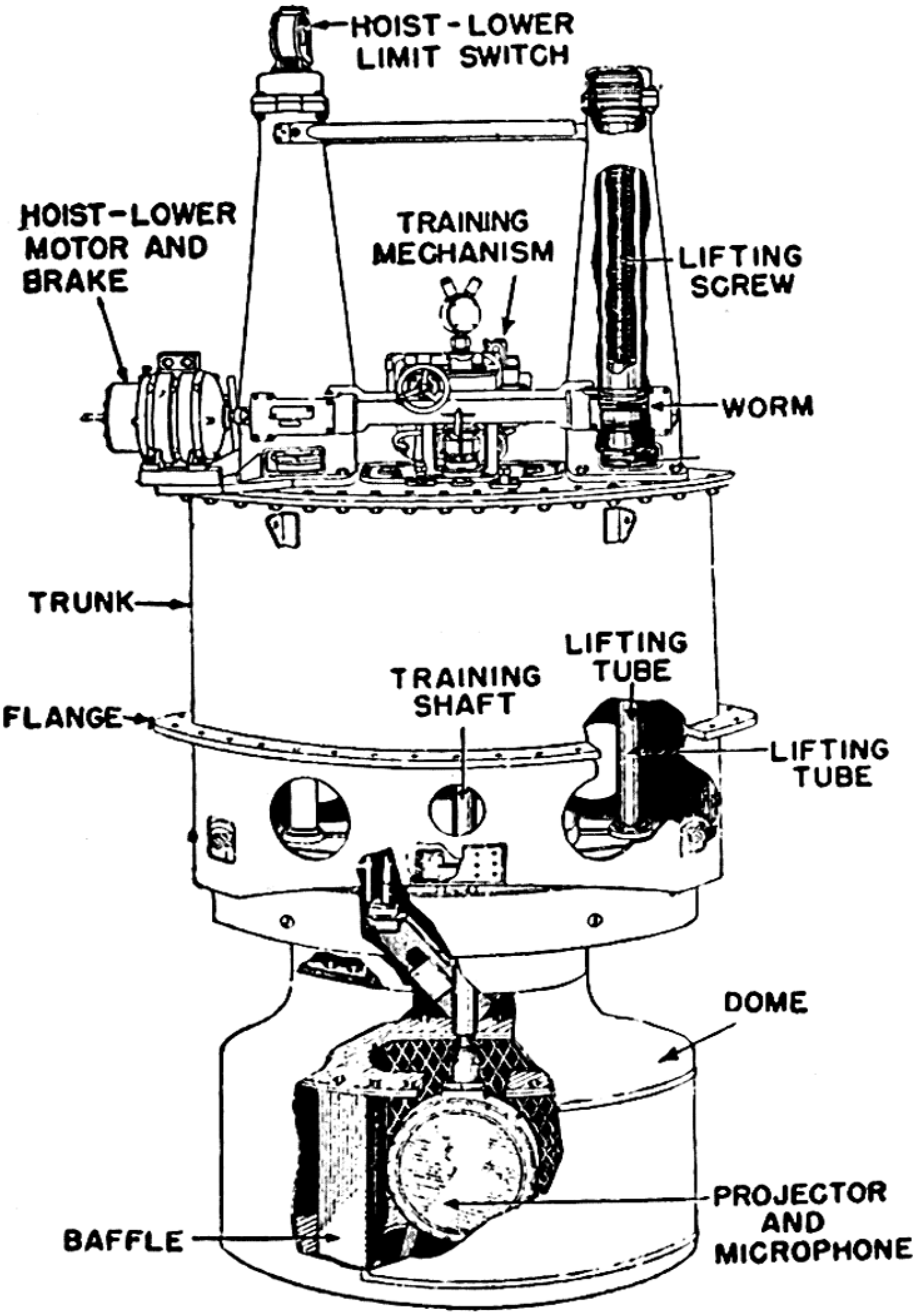

Fig. 9-11. Underwater section of submarine unit.

*Temperature Coefficient.* Using Nichrome, Pierce found that frequency was independent of circuit variations and that the temperature coefficient was

$$\frac{1}{f}\frac{\Delta f}{\Delta \theta}$$

which equals $-1.07 \times 10^{-4}$ degree centigrade

where $f$ = frequency

$\Delta f$ = change in frequency

$\Delta\theta$ = degrees centigrade changed

Temperature coefficients are usually large in magnetostriction bars but can be compensated for by methods already described. The concentric type appears to have some power advantages.

The change in frequency with temperature is caused by its effect upon elasticity and not upon other characteristics.

**Design of the Oscillating System—Electrical.** The commonest type of magnetostriction oscillator generator is shown in Fig. 9-12 and was originated by Pierce. The coil is loosely placed around the circumference of the rod. Oscillations are self-excited. The movement of the bar produces a voltage in the feedback coil that sustains the oscillation and without which the oscillator could not operate.

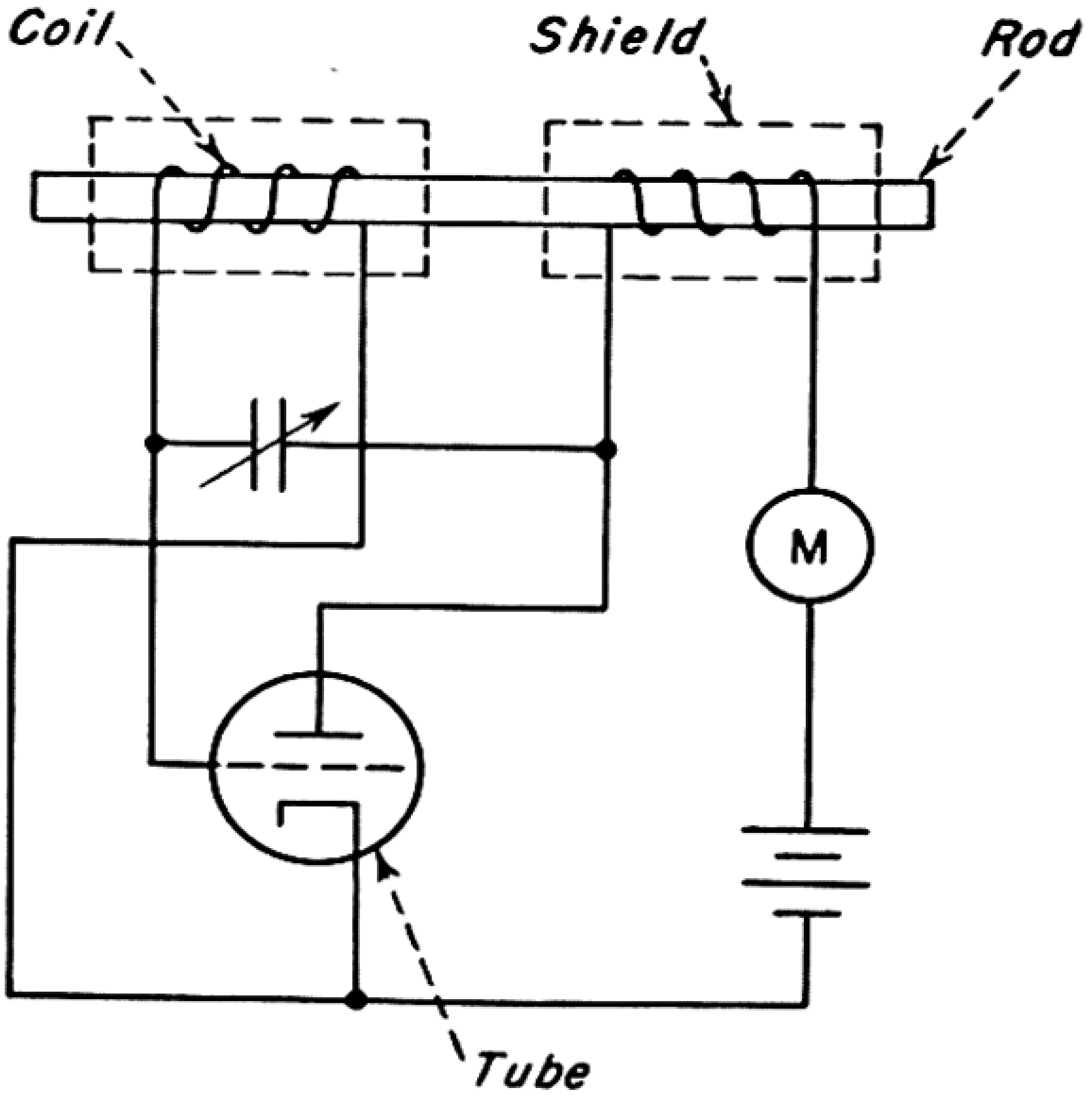

FIG. 9-12. Simple magnetostriction oscillator.

The coils are connected in a degenerative direction and are shielded from each other; *i.e.*, they are connected in a direction opposite to the usual manner for an electronic oscillator. The rod, however, provides feedback in the proper polarity.

When the rod is removed, the oscillator either may or may not continue to operate. If it does, it may be at a different frequency, since the frequency is controlled by the rod. Once the rod is inserted, the tuning condenser is not necessary, and the oscillator will actually continue to operate at the same frequency for various different settings of the condenser.

Generally the rod is inserted, and the condenser is tuned until a large jump in plate current (two to three tunes) occurs. At that point the condenser loses control and may be varied further without much effect.

Pierce stated that at 500 to 3,000 cycles it was preferable for the oscillator not to operate when the rod was out of its place and at 3,000 to 300,000 cycles it was desirable to have the oscillator run independently and merely be stabilized by the rod. In these cases, however, the usual degenerative connections were used. The conditions are valid for frequency-controlled oscillators.

The danger in using this circuit is that the system may be unable to maintain its oscillations when the rod loading is great.

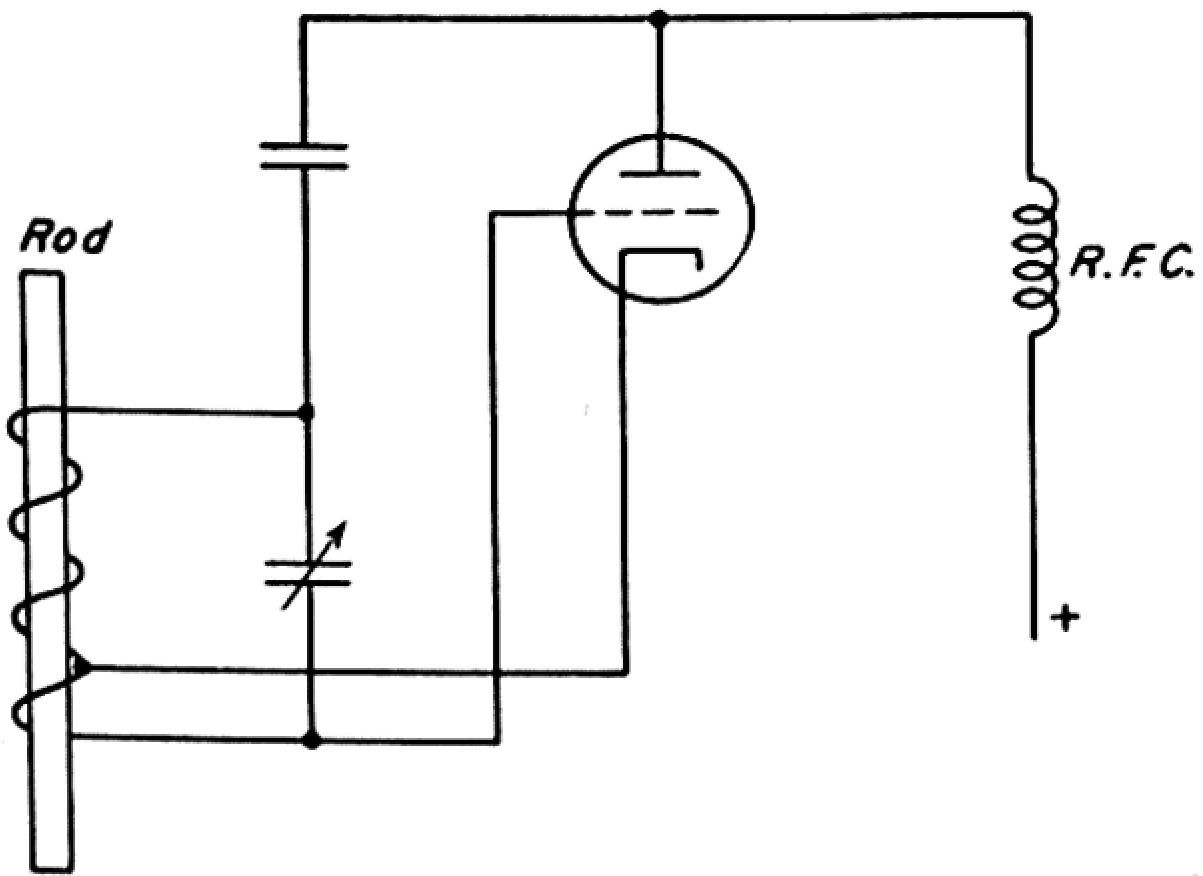

Fig. 9-13. Magnetostriction oscillator for rod activation.

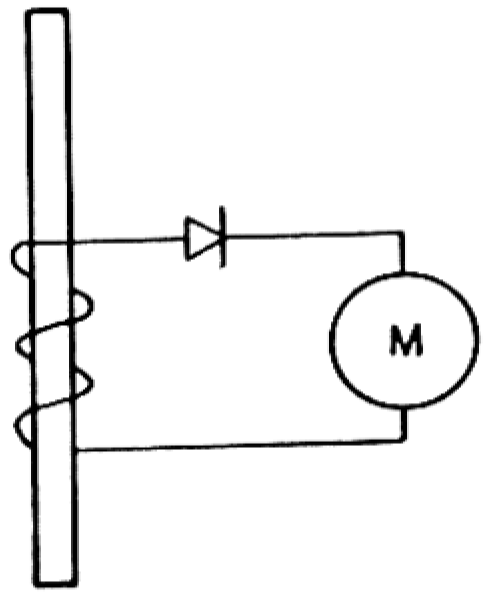

Fig. 9-14. Meter connection.

An alternate scheme is to use an ordinary oscillator connected in the usual regenerative manner to drive a rod for producing ultrasonic energy. There are various circuits applicable to this use. One of the simpler circuits is shown in Fig. 9-13. The rod is merely inserted and supported in the coil that constitutes the resonant circuit. Figure 9-14 is one method of connecting a meter for indicating the presence and amplitude of a signal. Either the rod is permanently magnetized, or the magnetization current is applied through an independent coil. In both cases the magnetostriction rod is used in the same manner as a crystal; it may either excite itself or be merely a driven element.

The action of the oscillator (Fig. 9-12) is described in greater detail, since it is characteristic of the entire class of units. The two coils are connected in the plate and grid leads, respectively, while the magnetostriction rod is clamped in its center. The meter in the plate circuit merely indicates the presence or absence of oscillations. The part of the rod in the plate side is driven by the output, while the other section in the grid side couples part of the energy back into the tube. The sections of coil are shielded from each other so that only the rod controls the feedback, and they are moreover connected degeneratively.

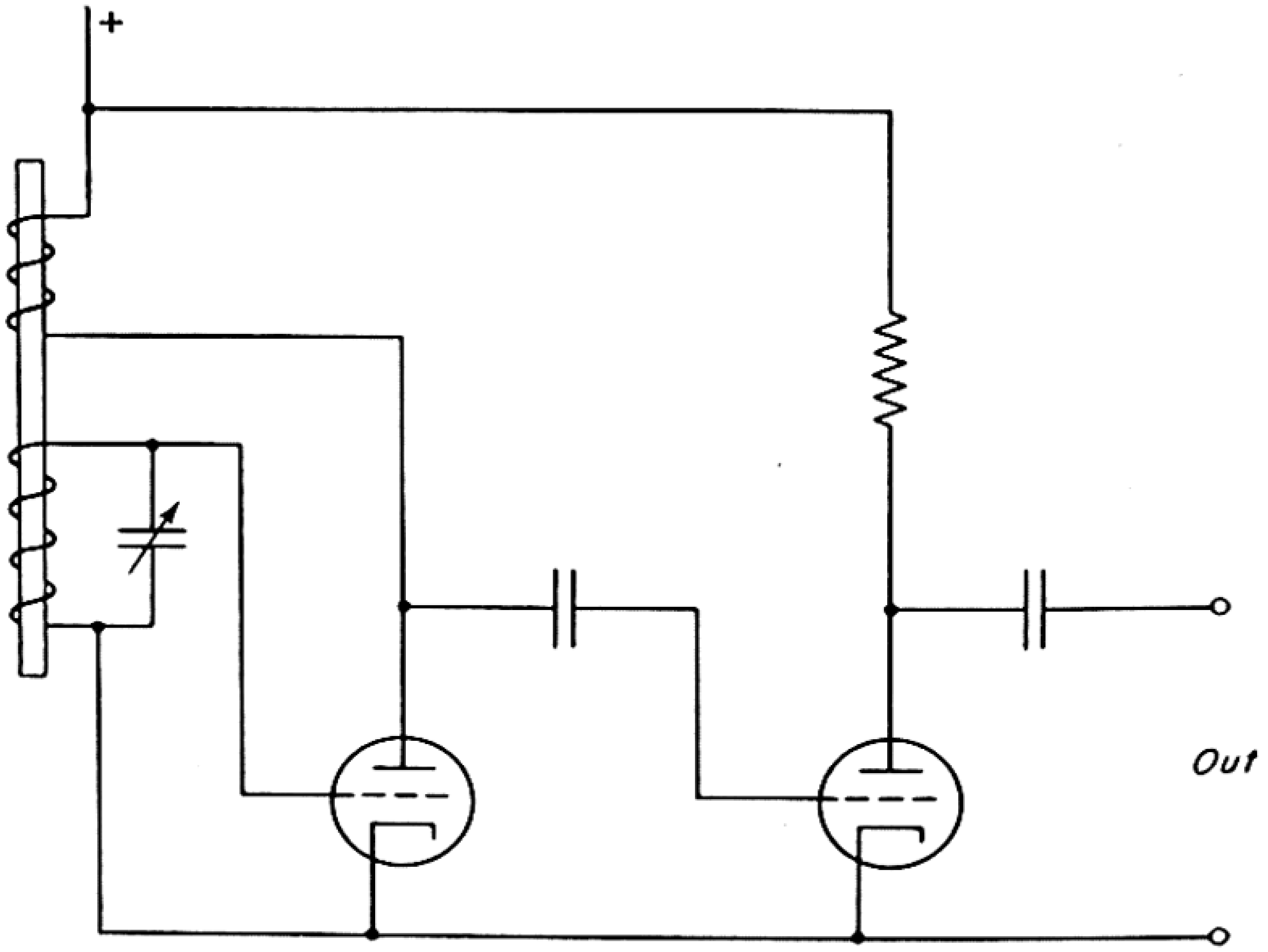

FIG. 9-15. Two-tube oscillator.

The frequency of oscillation is determined by $L$ and $C$, but especially by $L$.

The same effect can be produced in a two-stage unit in which the input coil is coupled into the first tube, amplified, and fed into a second tube. The output is then taken from the second tube (Fig. 9-15). This is, of course, for control purposes. A second magnetostriction unit must be coupled into the output if ultrasonic power is required.

Two tube units may also be used as magnetostriction units after the fashion of the multivibrator. The second tube feeds back to the first one through the magnetostriction system. This arrangement is not commonly used.

Magnetostriction receivers are merely audio- or radio-frequency amplifiers into whose input a transducer is coupled. One receiving circuit is indicated in Fig. 9-16. There are no special problems in designing such a unit in its simplest form. Alternate methods of coupling into the amplifier may be used.

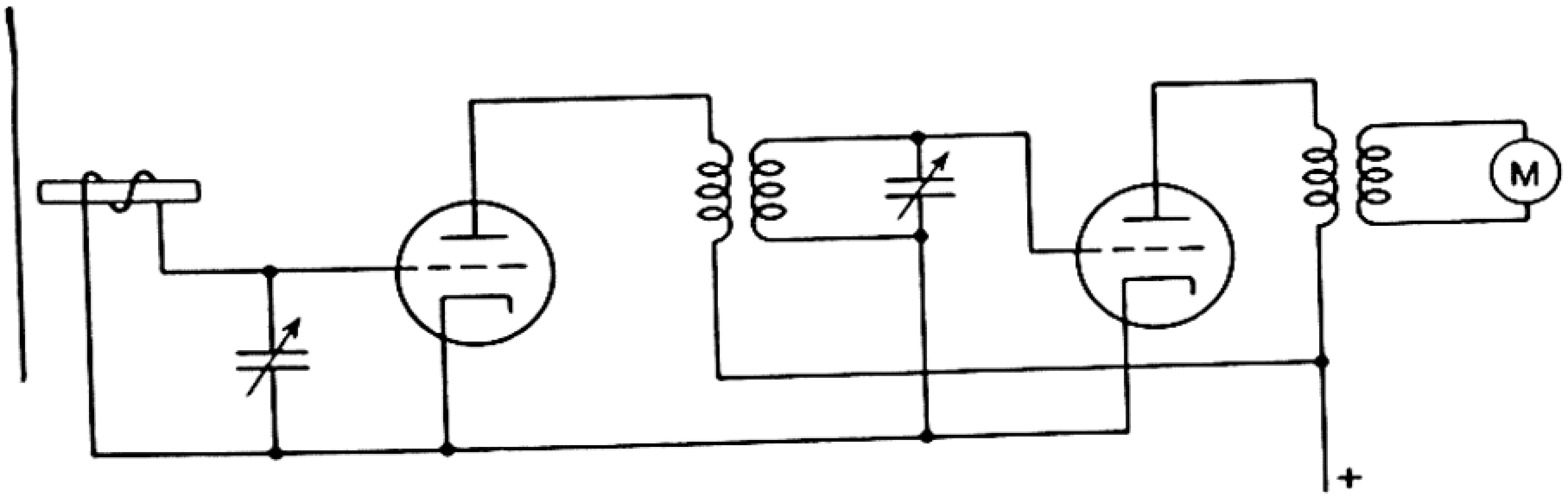

FIG. 9-16. Typical magnetostriction receiver.

The torsional type of magnetostriction transducer is also important. Torsion bars may be designed to operate in high temperatures and humidities without variation in their characteristics. The action is based on the change in reluctance when the bar is twisted torsionally in a field. In the same manner as the magnetostriction longitudinal type, torsion bars must be polarized if a linear output is desired.

One method of utilizing the effect is to pass a wire of magnetostrictive material between the poles of a horseshoe magnet. These units may be used as phonograph pickups. The stylus is fixed to the center of the wire, and pickup coils wound around it. The device gives excellent frequency response.[1]

**Miscellaneous Applications.** Another application closely allied to the submarine field is the sonobuoy.[2] This is a device which is floated in the ocean and picks up underwater sounds, such as enemy submarines, and transmits the signal through the air to patrol units. Broadcasting is carried out at individual frequencies for identification of specific buoys. The buoy is designed to sink after a few hours' service.

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[1] Stanley R. Rich, Torsional Magnetostriction Pickup, *Electronics*, June, 1946.

[2] Sonobuoy, *Electronics*, April, 1946.

The sonobuoys use magnetostriction units consisting of wire wound on a nickel cylinder. This transducer can generate about 3 $\mu$v, which is fed into an amplifier and broadcast. By identifying the broadcast signal the operator can tell the location of the enemy submarines.

Magnetostriction bars can also be used as filters and have been applied in many cases where electrical filters can also be used.

**Advantages.** The chief advantages of the magnetostriction oscillator are its cheapness and sturdiness. At low frequencies it is possible to get large amounts of energy from it. On the other hand the frequency range is too limited for use at high frequencies, it cannot be tuned sharply, and it is very sensitive to temperature.

## CHAPTER X

# PRACTICAL CONSIDERATIONS IN THE APPLICATION OF ULTRASONICS

Ultrasonics is rapidly becoming much more than a laboratory tool. It is accordingly important that some of its purely experimental and practical aspects receive some mention, especially since this information is of great value to the experimenter. Accordingly, some of the more recently developed aspects of ultrasonic application will be considered.

**Testing Materials for Flaws.** The most practical method of ultrasonic test is the echo method,[1] in which a pulse of ultrasonic energy is sent out and the time measured between this transmission and the reception of an echo. Such a system labors under the disadvantage that the apparatus is comparatively complex and expensive and also does not lend itself well to continuous production-line application up to the present time. Block diagrams and descriptions of such apparatus have already been given.

In setting up the pulse system, the length of the pulse should be adjusted according to the minimum distance of transmission. For example, if an operator were testing a part that was 1 in. thick, he would want the pulse to be a very small fraction of an inch. The time it takes for ultrasonic waves to travel 1 in. in steel or aluminum is about 8 $\mu$sec, so a good length for the pulse would be 2 $\mu$sec. If he were testing a part that was 20 ft long, the operator could have a pulse length of 5 to 10 $\mu$sec. This longer pulse enables him to get somewhat more power into the medium and therefore greater penetration. Above a certain amount, usually about 10 $\mu$sec, additional length does not seem to help the penetration and the only effect is to make the reflected signal appear broader.

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[1] B. Carlin, "Location of Internal Defects of Plant Equipment," American Gas Association, June, 1947.

For convenience, the indicating sweep may be designed so that any portion of it can be placed upon the screen and expanded to take up the entire visible space. This enables the operator to examine closely one particular part of the entire pattern. If the part being tested is 4 in. long, 4 in. of the sweep can be placed upon the screen and expanded. If only 1 in. is being tested, that length can be examined as a complete sweep. If a part in the center of a 30-in. block or even a 20-ft block shows some indication of a defect, the operator should be able immediately to position the significant section of the sweep at the center of the screen and expand it so that it covers the complete area. In cases where very thin films bonded together are to be tested, the difference in time between the reflection of a flaw and the reflection of the opposite side may be too slight to be noticed; in such cases through pulsed transmission can be used. However, the through method of testing is generally used with continuous waves, since the systems are cheaper and simpler.

The amount of transmission is also of value in testing whether or not a given part will absorb large amounts of the ultrasonic energy. If it is discovered that the amount of absorption to be expected is within certain limits for a standard part, defective material can often be differentiated from good material because of the fact that it will absorb more energy.

It has been noted that the amount of reflected energy depends upon the relation between the size of the reflecting surface and the wavelength at the particular frequency being used. This information gives a crude measure of the frequency which can be used in testing materials. Of course, it may not be necessary to detect flaws of the order of size of the wavelength. Lower frequencies can therefore be used as long as the flaws being detected are not too much smaller than the wavelength at the frequency of test.

For example, if the part is a very fine homogeneous structure such as steel or aluminum, it would be advisable to use a 5-mc frequency, which will find very fine flaws and will not be affected by the grain boundaries of the material. On the other hand, if the material is of somewhat coarser consistency and it is desirable not to have any interference from the structure, a 2½-mc frequency will be used. If the material is of very coarse structure such as brass or bronze, the higher frequencies will be reflected and scattered at the grain interfaces and will not be able to penetrate the material, so it would be advisable to use a frequency of 1 or ½ mc, which will pass these boundaries without destructive interference.

It is possible to get a measure of the grain size of a particular material by noting the amount of ultrasonic attenuation. However, the most important fact to remember is that as the interferences within the material become of the order of length of the wavelength at a particular test frequency, it gradually becomes impossible to penetrate the material at that frequency and it is then necessary to go to a lower frequency, which would have a corresponding longer wavelength and which is no longer interfered with. The best frequency from the point of view of general use is one of about 2½ mc.

**Distance Tested.** The pulsed ultrasonic tester can satisfactorily test for flaws lying between ½ in. and 30 ft from the face of the transducer. It is possible to find discontinuities closer to the surface than this, but more skill is required in interpreting the oscillograms. Greater distances can also be penetrated by raising the power output of the instrument. The size of the flaw that is found does not appear to be particularly influenced by its distance from the testing probe. In other words, the pulsed tester will find a No. 60 hole ⅛ in. in length at 1 or 2 in. from the testing unit and will find it practically as well at any distance between its testing limits. The amount of penetration does not depend upon the frequency of testing except in those cases where the ultrasonic waves are scattered by discontinuities in the material that are of the order of magnitude of the wavelength at which the testing is taking place. In other words, a particular billet may not transmit 5-mc ultrasonic vibrations because of the inclusions or grain-size characteristics, which possibly would interfere completely with the transmission of the 5-mc beam. Thus, one of the experimental uses of the ultrasonic test method might be in a metallurgical laboratory, where exact measurements of grain-size characteristics or plastic properties of particular metals or alloys are of interest. However, in

TABLE 10-1. ULTRASONIC WAVE PENETRATION INTO MATERIALS*

| Type material | Testing frequency, mcs | | | | Remarks |
|---|---|---|---|---|---|
| | 0.5 | 1 | 2.25 | 5 | |
| | Range, in feet unless otherwise marked | | | | |
| Steel: | | | | | Generally, depth of penetration into steel depends on the amount of working and processing of the material. Finer grain structure usually permits greater penetration |
| Ingots | 4–6 | 2–4 | 1–2 | 1 | |
| Billets, blooms | 5–12 | 6–8 | 3–4 | 1–2 | |
| Rolled | 22–25 | 22–25 | 10–25 | 5–8 | |
| Cold drawn | 22–25 | 22–25 | 16–20 | 7–10 | |
| Forged | 22–25 | 22–25 | 22–25 | 22–25 | |
| Tool steels | 22–25 | 22–25 | 22–25 | 22–25 | |
| Spring steels | 22–25 | 22–25 | 22–25 | 22–25 | |
| Stainless steels | | | | | |
| Steel castings: | | | | | Cast steels in the lower carbon range permit greater supersonic penetration |
| Carbon cast steels | | | | | |
| Low carbon | 15–20 | 15–20 | 10–15 | 7–10 | |
| Medium carbon | 14–18 | 14–18 | 8–12 | 5–8 | |
| High carbon | 13–16 | 13–16 | 7–10 | 4–6 | |
| Low-alloy castings | 17–20 | 17–20 | 12–15 | 7–10 | |
| High-alloy castings | 17–20 | 17–20 | 12–15 | 7–10 | |
| Cast iron: | | | | | "Scattering" of supersonic vibrations results where excessive porosity exists |
| Gray iron | 1–2 ft | 6–12 in. | 2–4 in. | | |
| Malleable | 7–10 ft | 7–10 ft | 3–5 ft | 6–12 in. | |
| Wrought iron | 7–10 ft | 7–10 ft | 3–5 ft | 6–12 in. | |
| Aluminum: | | | | | Coarse structure or porosity will interfere with penetration |
| Cast | 12–15 | 12–15 | 8–10 | 8–10 | |
| Extruded | 22–25 | 22–25 | 22–25 | 22–25 | |
| Worked | 22–25 | 22–25 | 22–25 | 22–25 | Finer grain structure permits greater penetration |
| Magnesium: | | | | | Physical properties similar to aluminum |
| Cast | 12–15 | 12–15 | 8–10 | 8–10 | |
| Extruded | 22–25 | 22–25 | 22–25 | 22–25 | |
| Worked | 22–25 | 22–25 | 22–25 | 22–25 | |
| Copper: | | | | | Coarse grain structure disperses vibrations |
| Cast | | | | | |
| Worked | 0–6 in. | 0–12 in. | | | |
| Brass and bronze: | | | | | Heat treatment will substantially extend limits of penetration |
| Cast, fine grain | 0–1½ | 0–1½ | | | |
| Cast, coarse grain | | | | | |
| Worked | 1–5 | 1–3 | | | |

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* Experimental values of approximate maximum depth of penetration in specific samples; not computed values nor absolute indication of penetration in any single material.

**TABLE 10-1. ULTRASONIC WAVE PENETRATION INTO MATERIALS** *(Continued)*

| Type material | Testing frequency, mcs | | | | Remarks |
|---|---|---|---|---|---|
| | 0.5 | 1 | 2.25 | 5 | |
| | Range, in feet unless otherwise marked | | | | |
| Lead | | | | | Physical properties absorb vibration |
| Nickel: | | | | | Greater porosity is usually present in cast materials |
| Cast | 1–3 | 1–3 | 1–2 | 6–12 in. | |
| Worked | 1–15 | 8–10 | 5–8 | 3–5 | |
| Monel—worked | 10–15 | 8–10 | 5–8 | 3–5 | |
| Gold—worked | 0–1 | 0–1 | | | Testing experience very limited |
| Silver—worked | 5–10 | 2–5 | 1–2 | 0–1 | Application usually confined to small pieces |
| Platinum | 7–10 | 7–10 | 3–5 | 3–5 | Figures are relative penetration. Sizes tested were not in this range |
| Tungsten | 7–10 | 7–10 | 3–5 | 3–5 | |
| Sintered carbides | 0–12 in. | 0–6 in. | 0–3 in. | 0–3 in. | Most of testing done at high frequencies because of nature of flaws to be found |
| Molybdenum: | | | | | |
| Sintered | 5–10 | 5–10 | 1–5 | 0–2 | |
| Worked | 21–25 | 21–25 | 21–25 | 15–18 | |
| Wood: | | | | | Direction of grain and amount of moisture in the wood affects transmission into medium |
| Hard | 0–8 in. | 0–4 in. | | | |
| Soft | | | | | |
| Masonite | 0–8 in. | 0–4 in. | | | |
| Plastics: | | | | | Depends on amount of filler in material |
| Vinylite | 6–12 in. | 6–12 in. | 6 in.–6 ft | 6 in.–6 ft | |
| Catalin | 6–12 in. | 6–12 in. | 6 in.–6 ft | 6 in.–6 ft | |
| Bakelite | 6–12 in. | 6–12 in. | 6 in.–6 ft | 6 in.–6 ft | |
| Lucite, or Plexiglas | 6–12 in. | 6–12 in. | 6 in.–6 ft | 6 in.–6 ft | |
| Oil | 24–25 | 24–25 | 24–25 | 24–25 | Indication of penetration limited only by capabilities of instrument |
| Water | 24–25 | 24–25 | 24–25 | 24–25 | |

routine testing, a crude indication of the character of the material being tested can be easily determined by trying various frequencies. The instrument must be carefully calibrated for the purpose. Unless very exact measurements are made, this method probably could not be used for routine tests of materials. Table 10-1 shows a chart of the distance in common materials that a low-power (1,000 volts peak to peak, 2-$\mu$sec pulse) ultrasonic tester will penetrate.[1]

**Materials Tested.** Ultrasonic methods are applicable to the testing of most metals and are particularly successful for metals that are reasonably homogeneous and close grained. These methods can also be applied to many of the denser plastics and glasses and can test other materials of lower density by using special frequencies. Tool steel is one example of a material that can be easily tested for flaws by ultrasonic methods. These steels can be used for cutting, shearing, or forming tools. The types of flaw ordinarily encountered are blow holes, bursts, flakes, inclusions, seams, segregations, and laps. All these are easily detected and located.

Forgings are also well adapted to ultrasonic test. Common examples of forgings are bearings, axles, shafts, turbine blanks, hammers, rotors, rolls, die blocks, billets, bars, piston rods, studs, pressure vessels, guns, etc. In every one of these cases the article can be quickly and easily tested.

Many ferrous castings can be tested. Steel castings take the form of cylinders, gears, wheels, rolls, etc., while iron castings are used on boat frames, gears, crankshafts, rolls, etc. Many castings can be satisfactorily tested, although as the grain sizes increase, it becomes more difficult to do a satisfactory job.

**Types and Size of Flaws.** An ultrasonic tester will find any appreciable discontinuity or inhomogeneity of elasticity in the material; thus it can find any holes or cracks within a solid mass of material and locate them exactly. It makes little difference exactly what causes the variation in elasticity; *i.e.*, a drilled hole and a blow hole indicate in the same manner. It should be realized that the flaws which the operator wishes to find must be larger than natural discontinuities or changes in grain size within the material. Within certain limits the ultrasonic unit is able to distinguish between reflections from small and large flaws by variations in frequency or by differences in the amplitude of the reflected signals, but it should be obvious to the operator that if the material is naturally full of porosities of ⅛ in. diameter, it will be difficult or impossible to find a $\frac{1}{16}$-in. flaw. Moreover, even if the material is full of $\frac{1}{16}$-in. inclusions, it may be impossible to distinguish ⅛-in. flaws. Ultrasonic waves will be affected by all of these segregations without regard to the difference in size. However, if the material is uniformly homogeneous except for the flaws, or if the flaws are larger than any natural discontinuity within the material, an ultrasonic instrument can usually locate them easily.

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[1] B. Carlin, Supersonic Examination of Materials, *Product Eng.*, October, 1947.

*Size.* The actual size of a flaw that can be found is rather difficult to state, but practical experimentation seems to indicate that the situation is somewhat as follows:

When the flaw is below a certain size, approximately the size of a No. 60 drill (.04 in. diameter) and about ⅛ in. long, the ability of an instrument to find it varies somewhat with distance; thus it is usually easier to find a flaw of this size 6 in. away than 6 ft away. As long as the dimension is smaller than that stated, it may roughly be stated that the ultrasonic unit will find a flaw of a size approximately one-tenth of 1 per cent of the thickness of the part. Whenever the flaw becomes larger than one of those dimensions, the relation no longer holds and the instrument seems to work on a more or less absolute basis. Thus it will find a ⅛-in. hole 1 ft away or 10 ft away in steel or aluminum with not too much difference in sensitivity.

In other words, if the discontinuity is greater than the diameter of a No. 60 drill, then the thickness of the part can be disregarded and the flaw will be located in almost any case.

*Orientation.* The orientation of a flaw can be very important if it is a very fine hairline crack of no appreciable thickness. If the crack is normal to the face of the transducer, it will not offer so much surface for reflection as otherwise. The section of a flaw in a plane parallel to the face of the crystal offers reflection. However, in a practical sense, this has never been a disadvantage, since there is almost always some component of the flaw in the proper direction to reflect energy to the transducer. Figure 10-1 indicates the action of a flaw lying at an angle to the crystal face upon the ultrasonic energy.

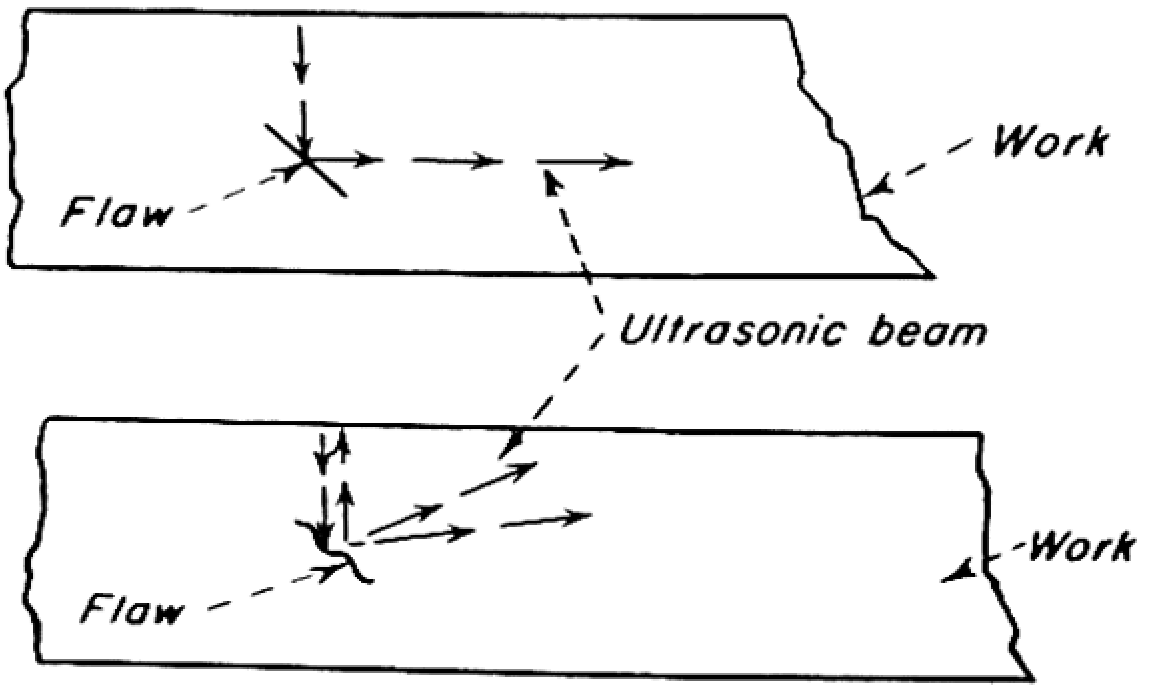
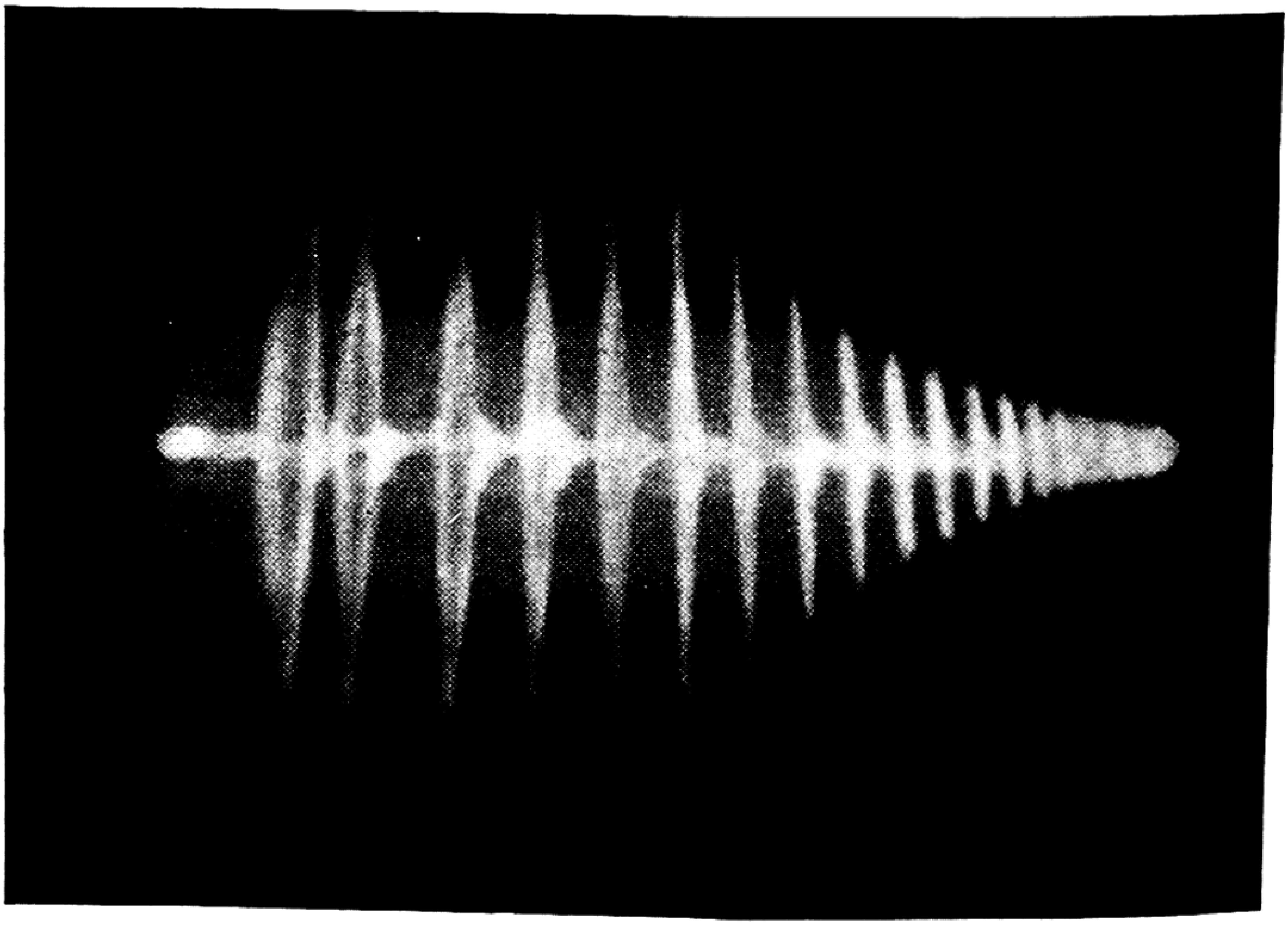


FIG. 10-1. Effect of flaws upon ultrasonic beams.

**Wall Thickness.** Ultrasonic testers can be used to measure wall thickness from one side by the reflection method in exactly the same manner as that used to find flaws. If the wall, however,



(a)

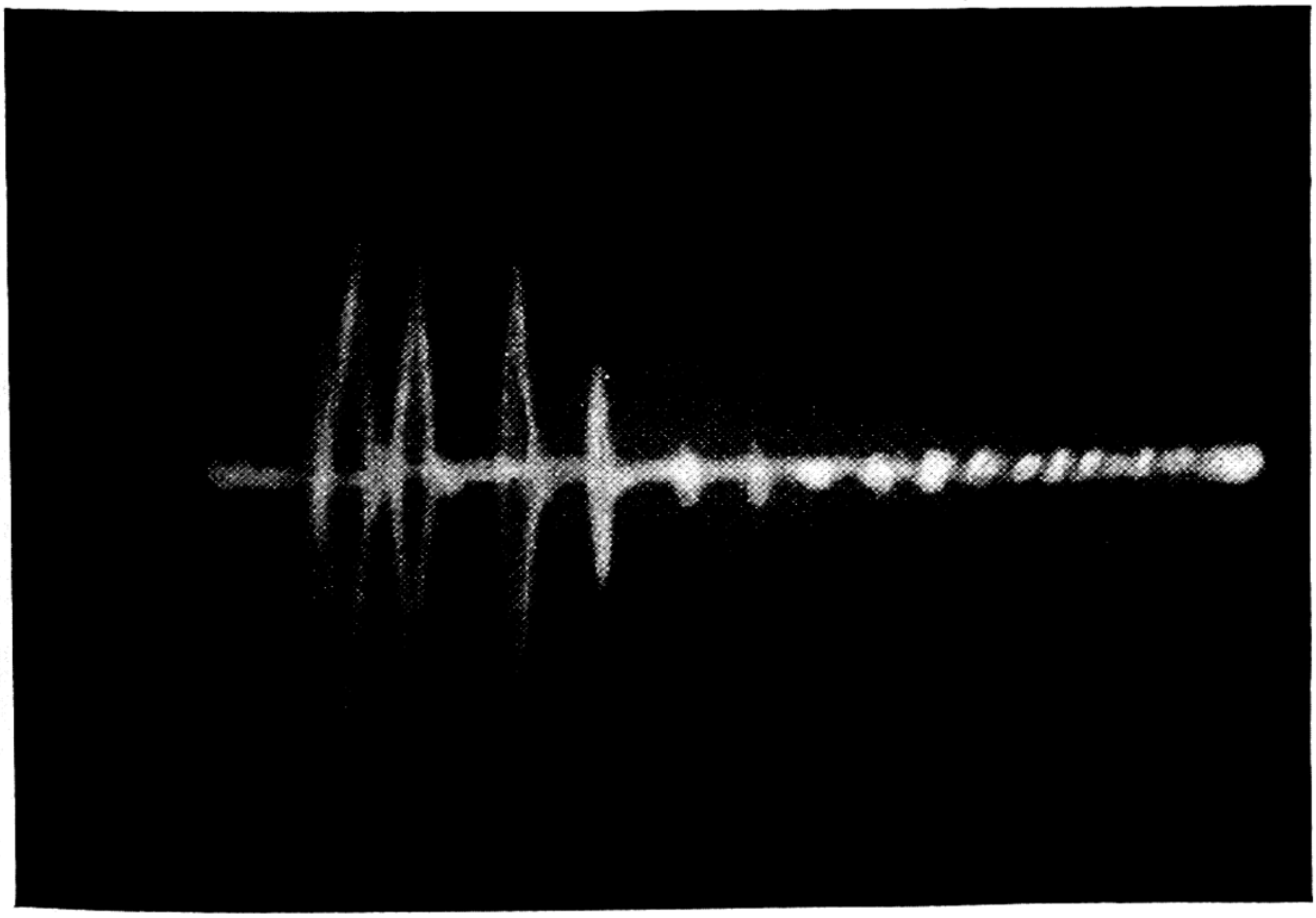
FIG. 10-2. Absorption patterns: (a) good material, (b) flawed material.

is less than ½ in. in thickness, the number of reflections per section of trace must be counted and the thickness computed by division into the total number of indications. For this reason it is difficult to measure walls less than ½ in. thick. In testing walls on tanks where the surface is very badly pitted or corroded on either side, the ultrasonic waves may be scattered and it will be difficult to get definite indications. Generally speaking, each new application must be tried before it can be definitely stated whether or not the instrument will operate satisfactorily.

One of the major problems in ultrasonics today is the successful application of the method to badly corroded or rusted parts.

Smooth walls of more than ½ in. in thickness can be satisfactorily measured by pulsed instruments.

**Absorption Testing.** The ultrasonic tester has been successfully used in the testing of materials by noting the absorption pattern. A typical pattern is indicated in Fig. 10-2. These



(*b*)

FIG. 10-2. (*Continued.*)

results can be correlated to differences in grain structure or internal cracks of the material. One successful application has been the testing of materials in plates where the thickness of the plate was too small to permit ordinary reflective thickness measurements. On a plate that is sound, a series of reflections of considerable height and spaced the proper distance will be clearly noted. When the plate is badly laminated, the reflections entirely disappear, thus giving a very strong and sharp indication of the defects. The laminated parts can be located exactly because of the directional characteristics of ultrasonics.

**Shape.** The chief disadvantage in ultrasonic testing is difficulty in testing small articles of involved shapes and sizes. Ultrasonic instruments can test a part wherever the surface on which the crystal is to be placed is at least 1/4 in. wide; but if the part is very small and has a large number of offsets and holes in it, it is practically impossible to interpret the results.

Ultrasonic testing in general, therefore, shows its greatest value in the examination of parts of very large size such as huge steel ingots where it is possible to shoot through 30 ft of steel and find a small flaw. Any part that is regular in shape and has a thickness in excess of 1 in. can easily be tested if the material permits ultrasonic transmission. On the other hand, a part under 1 in. thick can very often be tested as long as its shape is not too involved.

Curvature of the material, such as that in a pipe, is not a disadvantage, since either curved crystals can be used or special methods of using flat crystals have been successful. If the diameter is large, flat crystals can be used without any special couplant. If the diameter is small, it is usually easy to fit a curved crystal to it.

**Surface.** The surface of the material under test should be as smooth as possible. Where the material is very irregular, the irregularities have the effect of supporting the crystal away from the work so that it is not in intimate contact, and therefore the amount of energy transmitted into it is too slight for satisfactory testing. This may take place where the surface is badly pitted, rusted, or covered with heavy coatings of paint; and although general rules for ultrasonic testing can be set up, it is usually advisable to try the instrument on any particular surface in order to determine whether or not great enough penetration will take place. Where the surface is irregular and the transducer cannot get into contact, a suitable surface can be provided by smoothing with a hand grinder. This must be done on most sand cast surfaces. Machined surfaces are satisfactory within the limits of roughness given in Table 10-2.[1] Rolled or forged surfaces do not require extensive grinding but should be cleaned with a portable sander. Scale is not a great handicap to testing and may be left on the material as long as it is securely attached. As a matter of fact, it is not advisable to remove tightly adhering scale from steel surface, since the surface below a layer of scale may be wavy. The most desirable surface for routine tests is a ground surface with a tight scale adhering to it.

In most cases where the surface is concave, curved crystals must be used and flat ones are not applicable. Generally speaking, a special crystal or coupling device can be used with any surface of regular curvature. Where the curvature is very irregular, the surface must be smoothed off so that the crystal can fit against it.

The standard reference is from the General Electric Roughness Standards and from the Surf Check Roughness Standards. These refer to machined surfaces and are self-explanatory.

TABLE 10-2

| General Electric | | | Surf check and others | Acceptance for ultrasonics |
|---|---|---|---|---|
| Symbol | Roughness, $\mu$in. | | Roughness, $\mu$in. | |
| | Average | Average peak to valley | | |
| F4 | 63 | 220 | 60–80 | Preferred finish for detecting defects as small as 0.005 in. |
| F5 | 125 | 455 | 100–150 | Satisfactory for average testing for defects |
| F6 | 250 | 875 | 250 and up | Can be tolerated but not entirely satisfactory, as this finish may reduce sensitivity owing to poor surface contact |

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[1] *Ibid.*

**Use as a Test Instrument.** The engineer who finds himself in a position to examine materials may discover that the type of testing he has to do will fall into any one or all of three categories. (1) The first category is the testing of materials when they are in a raw or rough form. Thus if he has to build or machine a part out of steel or aluminum, he may buy those metals in bulk and wish to test the metal itself before he goes to the expense of machining it. He may also desire to test it periodically during the machining or working process to decide at which point flaws appear. (2) The engineer may desire to test parts that he has bought partly or entirely machined or built by an outside contractor or company. For example, the man responsible for building the airplane motor may buy his impeller wheels from an outside agency. He may wish to know whether these wheels are flawless or contain serious defects before he uses them in his machine. In a like manner he may desire to test other parts that have already been manufactured. These parts are referred to as *semifinished* or *finished*. (3) The third major use for testing may occur after the construction of an intricate mechanism. This may take place either immediately following assembly or periodically thereafter. An outstanding example of this is the testing of axles on heavy tractors or locomotives after the entire mechanism has been assembled. Not only may fatigue cracks appear after a period of service when it may be necessary to test for them without disassembling the mechanism, but the actual operation of pressing a wheel onto an axle may itself cause a flaw to appear.

**Testing Raw Materials.** The first category of test mentioned above is one in which ultrasonic testing is particularly efficient and where it may save many thousands of dollars in machining or other work. In the case where a part is to be machined out of a great mass of material, the machining operation may actually continue for a long time before a flaw is discovered that makes the entire part worthless. Ultrasonic testing has been widely used for testing billets and other masses of steel, aluminum, brass, magnesium, and other metals and has been successful in almost all of these applications. Straightforward ultrasonic testing is particularly useful in this type of application. Most of the bugs inherent in it have been ironed out, and applications may be approached with good expectation of success in almost every case.

**Testing Semifinished Parts.** Ultrasonic testing can be very successfully used in the testing of semifinished parts where those parts are of suitable size and shape. It has been used with good results on impeller wheels, drive shafts, and other objects where it was necessary to find flaws in the article prior to the final machining operation. It has been widely used for these applications by many large companies and is excellently suited to them.

**Testing Finished Materials.** In many cases a semifinished part need not be retested after it is completely finished, and it is sometimes impossible to do so, owing to the great irregularity of the shape of the finished article. In other cases it is more advisable to test the object after it is completed. One application is the testing of wing spars in airplanes. These spars are very long aluminum sections, which can be tested from one end. The entire spar is examined with one application. Where the spar is perfect, only the pulse and opposite side reflection will appear. Other reflections indicate a flaw at some point in the spar. Ultrasonic testing has also been used in testing propellers to see whether or not the internal reinforcements were correctly riveted and oriented, in testing bond between the silver coating on a bearing and the steel of the bearing, in testing bond of the cooling jacket in aeronautical engines, and in many similar applications.

**Fatigue Testing.** Ultrasonic methods are of particular value when used for locating fatigue failures. Testing can be carried out immediately after an article is assembled in order to see whether or not the assembly or machining process has contributed to the production of fatigue cracks within it. However, the commonest use is for periodic checks of materials that are under strain due to the way in which they are being used in order to determine whether or not flaws have developed. One example is the testing of locomotive axles and crankpins while they are in use on the locomotive. The same items can also be tested after the wheels are pressed off during a routine overhaul if that is easier for the operator. In a like manner ultrasonic testing has been used to test fatigue of steel plates used on the hulls of large ships, of backup rolls in use in steel mills, of shafts in large machines such as generators, and in many similar applications.

The testing of crankpins and axles is done from the ends (Fig. 10-3). Typical locations of flaws are also shown.

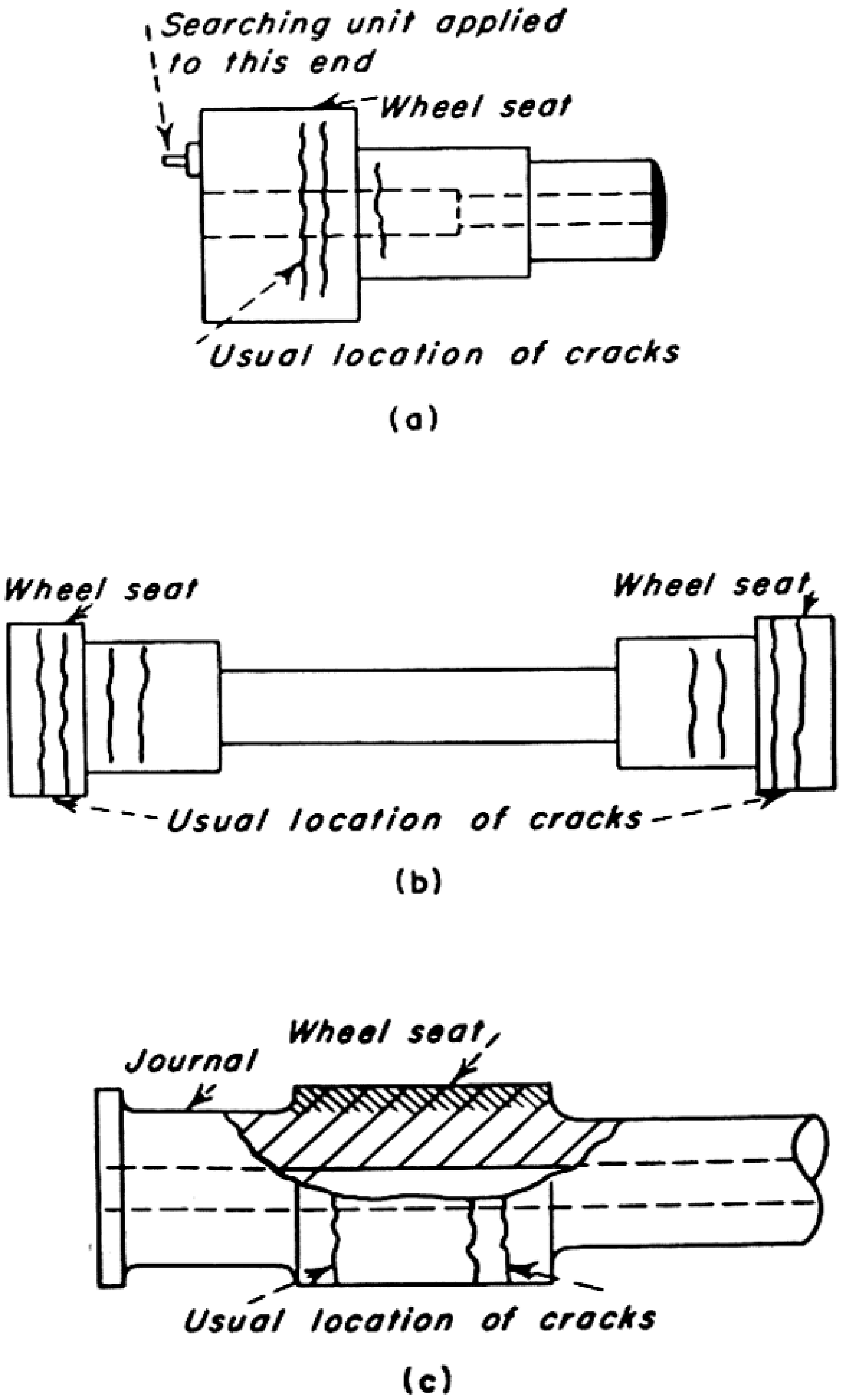


FIG. 10-3. The testing of axles and crank pins.

**Advantages and Disadvantages of Ultrasonic Testing.** Since ultrasonic applications have been explored only recently, often problems arise on which there is no prior experience and a solution must be worked out on the basis of work done in other similar fields. For this reason, it is particularly important that new ultrasonic problems be continually investigated, even though they initially appear to be outside the range of the method.

Applications of testing that appear impossible today probably will be solved within a comparatively short time.

One field still under investigation is the testing of materials that are characterized by a large grain size or many small dispersed cracks or flaws. The beam is scattered by the material and cannot penetrate it, and it is therefore impossible to test at the common frequencies. It is expected that special methods will be worked out to solve this and other problems.

It is also impossible to tell whether a bond is good or bad as long as it actually exists. Ultrasonics indicate only actual separations and will rarely show the quality of joints, etc.

Some of the chief advantages of ultrasonic testing lie in the fact that the size of the flaw located has little relation to the total amount of material penetrated. Thus a hole a few thousandths of an inch in diameter would be a very small percentage of a 5-in. block, yet the ultrasonic instrument can locate it as easily as on a much thinner block. Ultrasonic energy is as heavily reflected by a crack whose surfaces are closely pressed together as by one where there is a large separation. Flaws can be found in materials of great density where the flaw is visible only after sectioning and etching because of the very thin cross section of the separation.

An ultrasonic instrument can easily penetrate great masses of metal and is being successfully used on large steel billets to determine cropping points. Another application mentioned is the testing of railway axles and crankpins, in which a number of feet of steel must be penetrated while the axle is still on the locomotive. The highly directional characteristic of the ultrasonic beam makes it possible to investigate a particular part even when there are other parts surrounding it and when a very small portion of its surface is available for test.

Ultrasonic testing not only indicates flaws but locates them accurately owing to the time-marking system and to the fact that the beam is not very divergent. Thus when an article is tested by the method, not only are flaws found but the exact location of the flaws can be read directly from the instrument.

Ultrasonic testing is practically instantaneous. As short a time of application is required for a block 30 ft thick as for one

30 in. thick. The time of travel of the ultrasonic energy is calculated in microseconds, and instantaneous readings can therefore be taken, no matter how thick the article under test.

**Possible Theoretical Applications.** Since the advent of ultrasonic testing, a great number of inquiries and applications have been investigated. Parts are often sent for ultrasonic testing when the only prior knowledge appears to be that there may be some kind of flaw inside the material. Ultrasonic testing has provided an excellent nondestructive means of investigating the character of these materials. For example, it has never been possible before accurately to measure velocities of ultrasonics within solid materials, and it is interesting to note that many of the values obtained recently do not agree with those found by former experimenters. Certain qualities relative to the elastic constants of materials can be calculated from the results of ultrasonic application. The absorption of materials can be measured, and changes in absorption and other physical characteristics due to the effect of treatment can be easily noted. Ultrasonics can be used to verify the result of X-ray tests and to locate flaws that seem to be indicated by X ray.

**Technique for Close Testing.** When using pulsed ultrasonic testing, it is difficult to test within less than ½ in. because of the very short times involved. Certain techniques may, however, be worked out to circumvent this. One method is the use of total patterns to indicate differences in material characteristics. Another is the use of wedge methods. Still others include the use of delays, spacers, etc. However, in spite of all these systems it is difficult to test closer than ¼ in. from the surface in aluminum.

**Setting Standards for Ultrasonic Testing.** Many older methods of test have the advantage that by constant use, standards for testing materials are already set. This is not as yet true for ultrasonics. However, it is possible to set them. The procedure is more or less as follows: First, the size and frequency of crystal is chosen, *e.g.*, 1-in. square crystal at 2½ or 5 mc. The sensitivity is also chosen by locating certain standard holes in a standard metal block. The surface is standardized, and the test specified as satisfactory on certain distances of penetration.

Parts within those limitations are then checked and passed or rejected by comparison with the standard.

**Measuring Thickness by Ultrasonics: Resonance.** The pulsed ultrasonic tester can directly measure the thickness of a part by transmitting a pulse into it and measuring the time between transmission and reception for parts that require more than about 3 or 4 μsec of travel, *i.e.*, about ½ in. of steel or aluminum and up.

The resonance method can, however, satisfactorily test the thickness of parts between about 0.005 and 0.5 in. Besides measuring the thickness it can find flaws as well. However, its use as a flaw-finding mechanism is questionable, except in comparatively thin stock.

The resonance method can be used on any material that transmits vibrations satisfactorily. As with pulsed methods, the table of transmission can be used to indicate which those materials are. Inside or outside surfaces can be used as the test surface. Resonance instruments must be separately calibrated for every material. Besides metals, some glasses, plastics, and rubbers can be examined. As usual, when the material is nonconducting, the face of the transducer must be returned to ground by a foil facing, although some results can be obtained without that expedient.

The use of harmonics for resonance indications is not completely satisfactory, as it limits the thickest part easily tested to about ¼ in. By using harmonics, 4 in. can be tested, but the pattern is so complicated that to date these thicknesses are not usually attempted.

Resonance testers can most easily be used as flaw detectors by using them as simple comparators; *i.e.*, the transducer is placed on what is known to be a good part and then tried on a large succession of parts. The tested items are considered good if the pattern is identical. Resonance (as other ultrasonic means) will respond to extremely thin separations.

The indications will often completely disappear. This means merely that the energy is being diverted, as by an angular opposite face; absorbed, as by very viscous material; or scattered, by small inclusions. This action may be taken as cause for rejection, but the actual reason for the phenomenon may be unknown, and the method is therefore not to be recommended. Indications will usually be obtained in using resonance methods under conditions similar to those on which other ultrasonic methods are successful.

Resonance testing is particularly valuable in the inspection of bond, such as the silver bond on aeronautical bearings. The tester is set at the thickness of the entire part and indicates resonance; when the indication disappears, it shows that the part is defective.

Another method is to adjust the resonance instrument to the thickness of the bond only. In that case it will indicate only when the bond is separated from the main body of metal and show a defect then.

Bond between metal and other materials can be shown. However, when those materials are highly damping ones such as rubber or wood, the test must always be made from the metal side. The material fastened to the back of the metal will then always dampen out all reflections except when the bond is defective. This method can also be used with any other kind of ultrasonic testing depending for its action on reflected energy (Fig. 10-4).

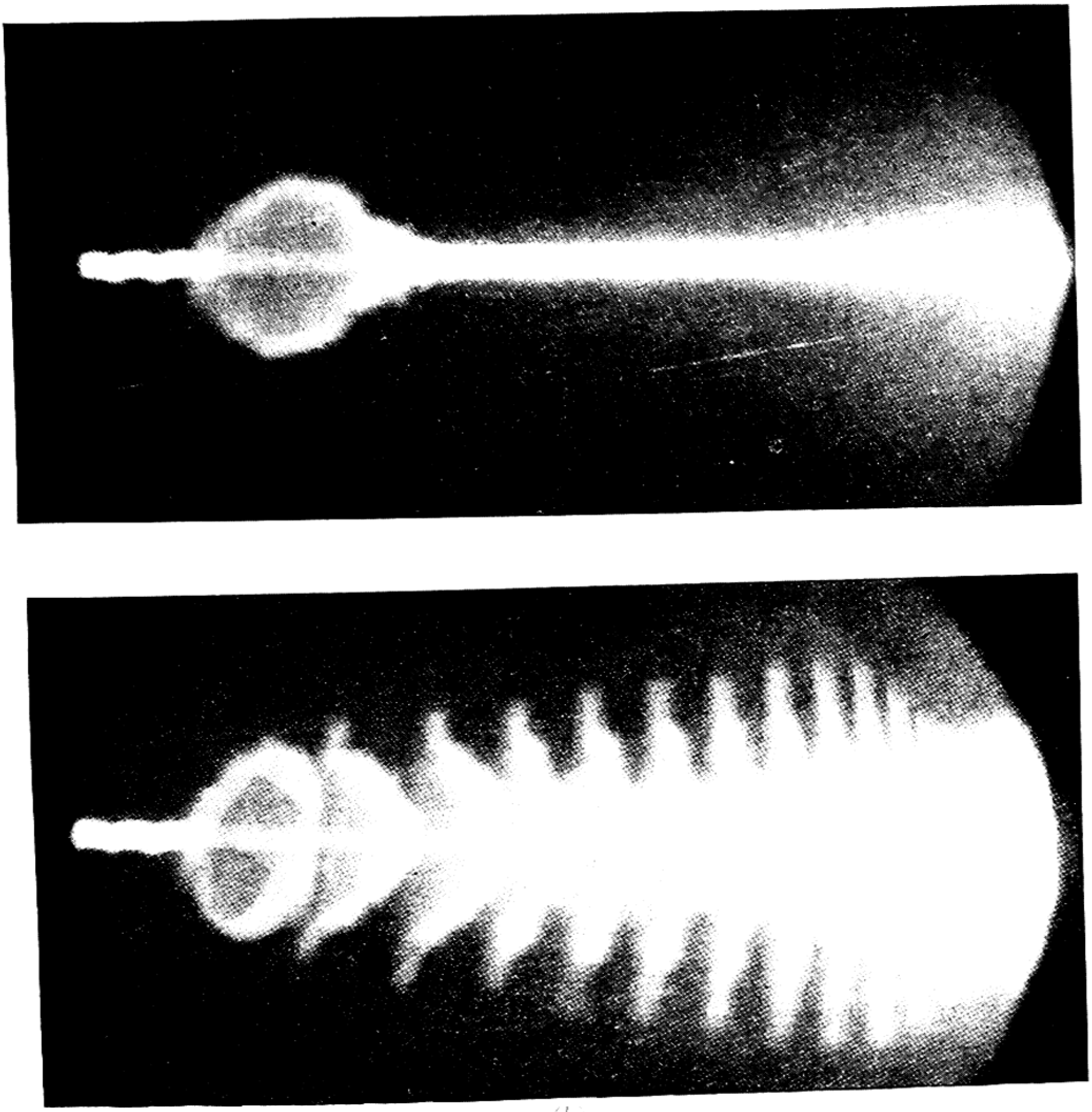
**The Transmission of Continuous Ultrasonics.** Systems that use continuous waves for testing are rarely used because of the troublesome reflections existing within the system, which make it nearly impossible to interpret results. However, modifications of the systems have been used when the flaws to be located were large enough to interrupt substantially the entire testing beam. In these cases the system may be operative.

The use of optical methods for indication is rarely practical because of their intrinsically cumbersome nature.

Swept frequency methods are not often used, since hash is troublesome, and they are not so successful as pulsed ones.

**Ultrasonic Agitation.** The application of ultrasonics to chemistry is not discussed here from the point of view of the chemist. However, agitation systems are becoming more and more common, and intensive research in these fields has been carried out.

Although a great deal of material has been published on the subject of ultrasonic agitation, the more practical aspects of the field are still largely unexplored. The generating units are standard, and the precautions taken when working with any high-power system or transmitter should also be taken with ultrasonic ones. The voltages used are often lethal, and suitable interlocks should therefore be provided on the cabinets. Once



(*b*)

FIG. 10-4. Damped ultrasonic waves: (*a*) damped, (*b*) undamped.

this is done, the main consideration is the design of the crystal holder and agitating tank. From what has already been said it is obvious that these units must be able to withstand a breakdown voltage of at least as much as the voltage impressed across the crystal. The coating of the crystal should be kept back from the edge so that flashover will not take place. The supports should be made of steatite or a similar material that has a high resistance to voltage breakdown. Clamps for holding the crystal in place should be glass or steatite. Leads to the crystal and connections should be made in a manner that takes into account the voltage values.

**Television.** It is possible to obtain a television picture by modulating a light ultrasonically. The basis of such a system is the ultrasonic cell, which consists of a body of liquid through which the ultrasonics pass and, in turn, modulate the light. By using the phenomenon of light diffraction, the ultrasonic system gives a much greater illumination than most other television methods. The design of these systems is a science in itself and will not be considered in detail here.

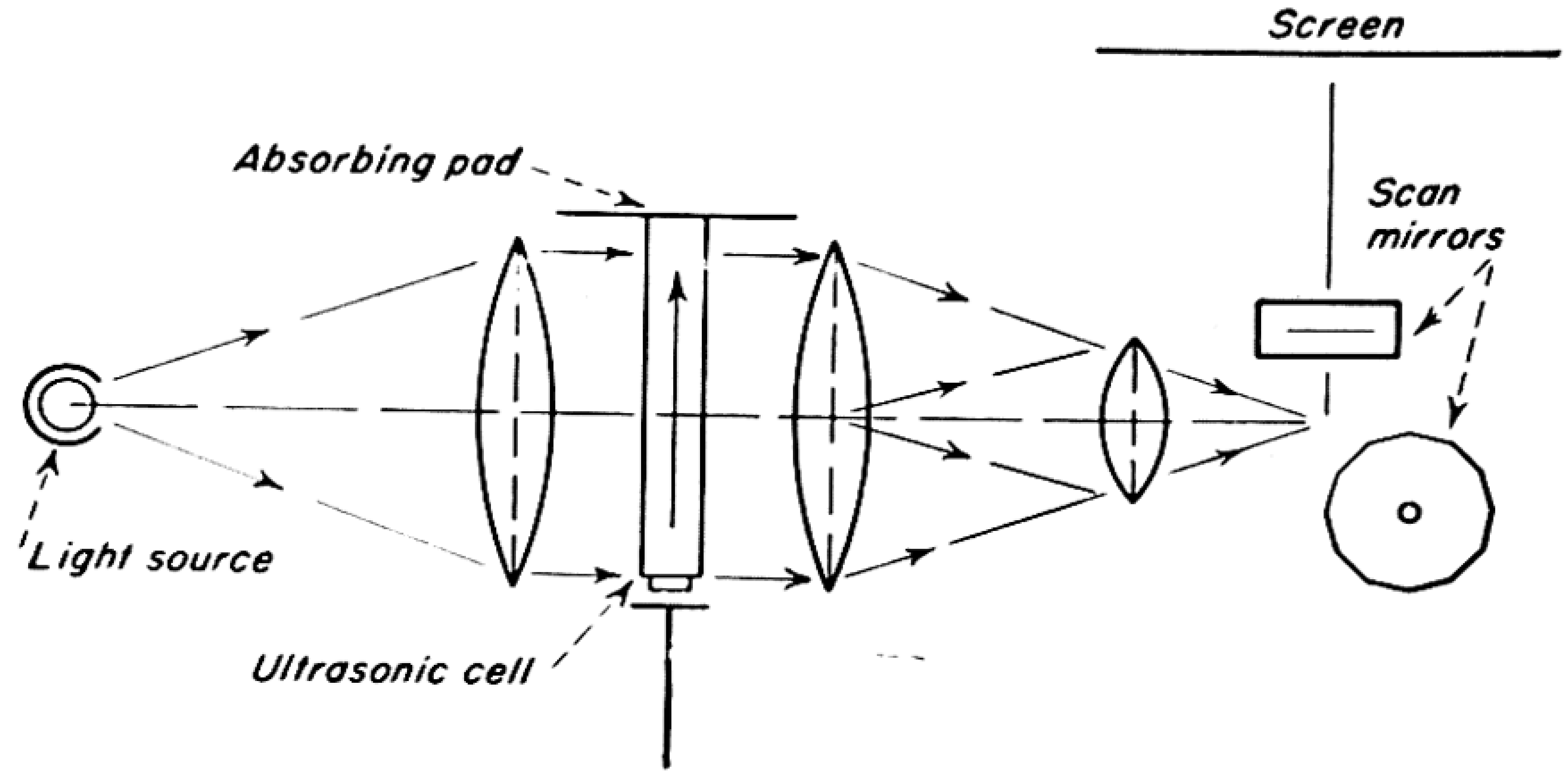


FIG. 10-5. Ultrasonic television system.

The amount of voltage exciting the unit controls the illumination directly; when this voltage is modulated, the intensity is also modulated.

The further design of the ultrasonic television system seems to offer great possibilities once the system becomes simple enough and entirely electronic. However, ultrasonic systems are not popular to date in this country. Figure 10-5 indicates a typical system of the ultrasonic type.

**Signaling.** The field of sonic and ultrasonic signaling has been exhaustively investigated during the war. In air, the system has certain great disadvantages, which practically prohibit its general uses. In water, possibilities of practical systems exist and will be found in the literature. These are more commonly used in wartime. The principles already described in connection with testing can be applied to such signaling.

**Photographing Cathode-ray Screens.** Many devices using ultrasonics utilize the cathode-ray tube as an indicator. It is accordingly useful to maintain records of results by photographing the screen during or after test. A simple mechanism can be used to take such pictures. This is shown in Fig. 10-6. The camera is positioned over the screen and held in a jig, which fixes its focus on the fluorescent material. A cone of black material is added to keep out light, and a peephole placed in it so that the operator can watch the pattern while taking a picture. Naturally, many alternate methods can be used. A set of exposures for the Pl screen using ordinary film in the 35-mm camera is also given (Table 10-3).

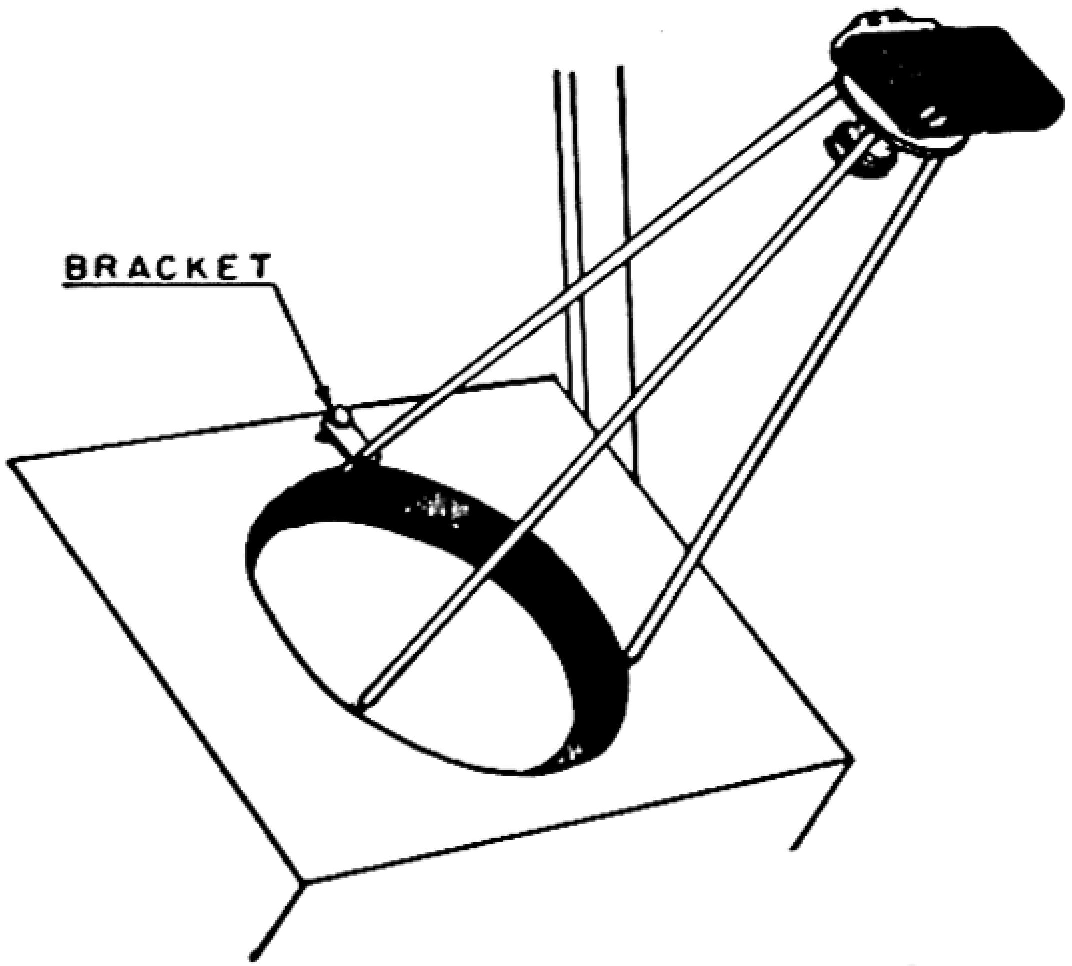


FIG. 10-6. Photographing the cathode-ray screen.

With this method of using the cathode-ray tube, successful pictures can be taken for future reference and can be interpreted upon examination at any time, since the marks on the sweep are permanently recorded.

**Medicine.** Although ultrasonics has been suggested for medical applications as knifeless surgery and diathermy, it has never been widely used for these purposes. It is, however, possible that further research in this field will be done in the near future. No known work in this field indicates that it is being successfully used at the present.

TABLE 10-3

| Kind of film, 35 mm | Weston rating | Grain | Speed | No. of exposures | Lens setting | Average exposure and aperture openings |
|---|---|---|---|---|---|---|
| Super XX. | 100 | Fine | Fast | 20 or 36 | Infinity or prescribed setting when using adapter lens | 5 sec at F/2<br>10 sec at F/4.5 |
| Photoflure. | 600 | Medium fine | Extremely sensitive to green | 36 |  | 2 sec at F/2 |
| Plus X.... | 50 | Fine | Slow | 20 or 36 |  | 15 sec at F/4.5 |

# INDEX

A

Absorption, 51
  testing by, 251
Acoustic impedance, 118
  matching of, 119
Activity, crystal, 77
ADP (ammonium dihydrogen phosphate) crystal, 79
Aerosols, 220
Agitation, 200, 260
  action of, 203
  frequency, 201
  history of, 202
  holders for, 104, 209
  magnetostriction in, 214
  measurement of power in, 211
  power output in, 210
  pressure in, 201
Air-gap resonance, 86
Andalikiewicz, B. A., 131
Anderson, M. A., 210
Andrews, B. A., 153
Angerer, 14
Angular transmission, 39, 40, 157, 164, 175
Antinodes, 30
Attenuation, 30

B

Band width, 195
Bar, 47
Barrett effect, 223
Beams, 10, 11
  examination of, 12
  interrupting of, 96
  limiting of, 99
Beats, 53
Bechmann, 82
Becker, H., 83
Behun, A., 120
Bergmann, 1, 16, 46, 60, 71
Bez-Bardili, W., 158
Biological effects, 217
Biquard, 45
Bjerknes, C. A., 215
Boyle, R. W., 14, 49, 54, 216
Brandt, O., 215, 220
Brillouin, 45, 122
Button, crystal, 84

C

Cable connection, 106
Cancellation effects, 54
Carlin, B., 39, 100, 133, 174, 243, 246
Cathode-ray tube, photographing of, 263
  in pulsed systems, 186
Cavitation, 54
Cermak, P., 48
Chemical effects, 216
Chladni patterns, 60
Claus, B., 218, 220
Coagulation, 214
Coile, R. C., 230
Compound oscillators, 70, 72
Continuous waves, 30, 137
  generators for, 149
  history of, 137
  oscillators for, 148
  receivers of, 150
  signaling, 155, 260
Crystals, 55
  activity of, 77
  ADP, 79
  cleaning of, 69
  combination of, 71
    mosaics in, 72
    stacked, 71
  curved, 75
  damping of, 87
  design, of longitudinal-wave, 65
    of shear-wave, 66
  directional characteristics of, 67
  facing for, 69
  history of, 55

Crystals, matching of, 103
  plating of, 68
  preparation for mounting of, 81
  special cutting of, 79
  stacked, 72
Curie, J., 58
Curie, P., 58
Curves, 31
Czerlinsky, E., 48

D

Debye, P., 45
Degassing, 216
Delay circuits, 182
Density, of quartz, 65
  of Rochelle salt, 79
Desch, C. H., 174
Detection of ultrasonics, 28
  radiometer for, 29
  resistance methods in, 28
Diaphragms, magnetostriction, 234
Differentiation, 184
Diffraction, of light, 45
  systems of, 46
  in ultrasonics, 18
Diopters, 77
Dispersion, 214
Dissipation, 24
Doppler effect, 47, 53, 156
Drop tests, 131

E

Echo method, 25, 243
Emulsification, 203, 215
Energy, 25
  loss of, 24
  measurement of, 25
Epstein, L. F., 210
Ernst, P. J., 106
Erwin, W. S., 128
Evans, R. J., 236
Extensometer, 223

F

Facings, 69
Fadenburg, 14
Fatigue testing, 255
Fessenden, 162
Fillers, 90
Firestone, F. A., 16, 88, 135, 171, 173, 189
Flaws, orientation of, 249
  types and sizes of, 248
Focusing, 75, 106, 210
Forster, 218
Fourier analysis, 33
Fox, F. E., 108
Frequency, 16
  variation in, 160
Freund, H., 210, 220
Freundlich, 24

G

Gas effects, 220
Gating, 197
Generation, 27
  crystal in, 28
  magnetostriction in, 27
  spark gap in, 27
  whistles in, 27
Gruetzmacher, J., 75, 105
Guillemin effect, 222

H

Hahnemann, W., 169
Harden, L. R., 210
Harmonics, 63
Harvey, E. N., 215
Hayes, H. C., 127
Henvis, B. V., 16
Hershberger, 122
Hippel, von, A., 211
Holders, 81
  for agitation, 104
  for angular propagation, 92
  for interferometry, 107
  in liquids, 95
  liquids to solids, for transmitting through, 93
  longitudinal-wave, 84
  magnetic, 92
  for microscope use, 108
  for resonance testing, 107
  for shear or surface waves, 94
Holste, 218
Hopwood, F. L., 217
Hubbard, 122
Hughes, Henry, and Sons, 174
Hydrodynamic flow, 25

I

Impedance, acoustic, 118
  characteristic, 120
  matching, 119
  motional, 53
Indication methods, 161
Indicator for oscillations, 74
Interferometer, 107, 121, 223
  Rochelle salt in, 122
Interrupter, beam, 96

J

Jetter, U., 219
Joule, J. P., 222

K

Kallmeyer, W., 232
Kirchhoff, G., 52
Klein, 122
Knott, 8
Kruse, F., 144
Kundt, 28, 220

L

Labaw, L. W., 76
Langevin, P., 55, 56, 162, 202, 217
Le Chatelier, 224
Lehmann, J. F., 49
Lenses, 106, 146
*LH* crystal, 79
Lippmann, 60
Longitudinal direct effect, 59
Longitudinal waves, 4, 14, 37
Loomis, A. L., 104, 122, 202, 217, 218, 221
Lucas, 45
Lycopodium, 29

M

Macelwaine, 8
Magnetic holders, 92
Magnetostriction, 127, 222, 225
  agitation in, 214
  Barrett effect in, 223
  for control of frequency, 225
  design of, 229
  diaphragms for, 234
  direct effects of, 222
  electrical considerations of, 238
  Guillemin effect in, 222
  inverse effect in, 224
Magnetostriction, materials for, 226
  miscellaneous effects of, 224
  Nagaoka-Hondo effect of, 224
  oscillator control in, 225
  output of, 225
  resonance of, 127
  rod in, 227
  shape of, 230
  Villari effect of, 224
  Wertheim effect of, 224
  Wiedemann effect of, 223
    second, 224
Mahoux, G., 219
Marconi, 232
Marinesco, N., 218
Mark, H., 216
Markers, 185
Mason, W. P., 50, 103, 134, 160
Materials, shape of, 252
  surface of, 252
  tested, 248
Measurement of velocity in solids, 13
Medicine, 263
Metallurgical applications, 218
Meyer, 47
Michelson, 223
Microscope, 108
Modes, 60
Mohs' scale, 57
Morgan, A. R., 76
Morris, W. E., 99, 161
Mosaics, 72
Motion, simple harmonic, 31
Motional impedance, 53
Mower, R. J., 211
Muhlhauser, 137, 157

N

Nagaoka, H., 224
Nicholson, A. M., 56
Nodes, 30
Ny Tse Ze, 61

O

Ocean signaling, 26
Orientation, 23
Orlich, 163
Oscillators, 148
  compound, 70, 72
  indicator for, 74

Oscillators, resonance in, 125
Output, 70
Oyama, H., 207

P

Particle equations, 36
Photographing of cathode-ray tube, 263
Pierce, G. W., 16, 121, 225, 232, 233, 235
Piezo axis, 58
Piezoelectric effect, 58
  limitations of, 61
  reverse, 60
Piezoelectric modulus, 61
  tourmaline, 66
Pin mounting, 83
Plane waves, 9
Plotting the crystal, 74
Pohlmann, R., 161
Polar axis, 58
Polymers, 217
Poulsen arc, 202, 204
Power output, 210
Pulse forming, 186
Pulse generation, 188
Pulsed systems, 162
  cathode-ray tube in, 186
  delay circuits in, 184
  electronics in, 178
  gas tubes in, 188
  high-vacuum tubes in, 191
  history of, 162
  markers in, 185
  receivers in, 194
  sweep in, 180
  testing materials in, 171
Pyroelectricity, 79

Q

Quartz, 55

R

Radar, 165
Radiometer, 29
Rassweiler, G. M., 128
Rayleigh, 36, 216
Rayleigh waves, velocity of, 14
Receivers, 150
  gating, 197
  for pulses, 194
Rectilinear propagation, 9
Reflection, 18, 20, 21
  from obstacles, 22
Reflectogage, 128
Reflectors, 106
Reflectoscope, 171
Refraction, 23
Resolution in system, 194
Resonance, 107, 109
  air-gap, 86
  excitation of, 118
  indication of, 123
  interferometry in, 120
  limitations in, 135
  magnetostrictions in, 127
  oscillators in, 125
  and submarine apparatus, 120
  systems of, 124
  testing materials by, 118
  thickness measurement by, 115, 259
Rich, S. R., 241
Richards, W. T., 215, 219
Richardson, 162
Rochelle salt, 56, 74, 78
  Young's modulus in, 79
Rock, G. D., 108
Rogowski, F., 24
Roughness Standards, General Electric, 253
  Surf Check, 253

S

Saxton, 26
Schilling, 26
Schmid, G., 219
Schoeneck, H., 48
Sears, F. W., 45
Seismic signaling, 167
Shape of materials, 252
Shear waves, 3, 5, 37
Shielding of apparatus, 161
Shraiber, D. S., 49, 91, 98, 113, 132, 143, 144
Signaling, 155, 263
  air, 26
  ocean, 26, 157
  seismic, 167
  wires for, 27
Sine wave, 31
Smith, F. W., 19, 105, 204, 214, 218
Sohon, 8
Sokolov, S. J., 45, 70, 73, 140, 141, 142, 204, 219

Sollner, H. K., 24
Sonar (Sound Navigation And Ranging), 168
Sonigage (General Motors'), 128
Sonobuoy, 241
Sound ranging, 26
Spectrum, ultrasonic, 2, 46
Spherical waves, 9
Spring mounting, 91
Standing waves, 112
  in continuous-wave systems, 160
  elimination of, by absorption, 134
    by frequency variation, 132, 160
    by pulsing, 134
    by sensitivity control, 134
    by spacing, 133
  ratio of, 119
Standoffs, mechanical, 89
Stokes, G. G., 52
Straubel, H., 64
  contour, 64
Striation, 48
Stroboscopic effect, 48
Struthers, F. W., 90
Stumpf, P. K., 19, 105, 204, 214, 218
Submarine signaling transducers, 105
Superposition, 16
Surface waves, 6, 38
Sweep, 181

T

Tanks, 97
Taylor, 14
Teeter, G. E., 26
Television, 262
Temperature coefficient, 62, 237
Tesla coil, 208
Test instruments, 254
Testing, close, 258
  distance of, 245
  of finished parts, 255
  of materials, 243
  of raw materials, 254
  of semifinished parts, 255
Thermal detection, 29
Thickness table, 67
Thin plates, transmission through, 49
Timoshenko, S., 36
Toepler, A., 48
Tourmaline, 66
Transducers, 30
  submarine signaling, 105
  tuning of, 157
Transformation of waves, 7, 8, 40, 209
  in liquids to solids, 43
  in solids, 43, 218
  in solids to gas, 44
  in solids to liquids, 44
  in waves, 7, 8, 40, 209

U

"Ultraschall, Der," 1
Ultrasonics, advantages of use of, 256
  definitions of, 1
  standards in, 258
  theoretical applications of, 255
  theory of, 35
Urick, R. J., 26

V

van der Waals bonds, 217
Velocity, 12
  group, 13
  in liquids and gases, 15
  of longitudinal waves, 14
  measurement of, in solids, 13
  phase, 13
  of Rayleigh waves, 14
  of shear waves, 14
  signal, 13
  theoretical considerations, 35
Villari effect, 224
Voigt, W., 60

W

Wall-thickness measurement, 250
Wave motion, 2
  complex, 33
  continuous, 30, 137
  longitudinal, 4
  modulated, 30
  shear, 5
  simple harmonic, 31
  spherical, 9
  standing, 160
  surface or Rayleigh, 6, 14, 38
  transformation in, 7, 40
  types of, 3, 35
Wave train, 30, 34
Wavelength, 16, 30

Waves, complex, 33
  continuous, 30, 137
    (*See also* Continuous waves)
  longitudinal, 4, 14, 37
  plane, 9
  Rayleigh, 6, 14, 38
  shear, 3, 5, 37
  sine, 32
  spherical, 9
  standing, 112
    (*See also* Standing waves)
  surface, 6, 14, 38
  transformation of, 7, 8, 40, 209
    (*See also* Transformation of waves)
  transverse, 3
Waves, types of, 3, 35
Wenco, 101
Wertheim effect, 224
Wiedemann effect, 223
Willard, G. W., 46
Williams, R. C., 68
Wire, propagation through, 27
Wood, R. W., 104, 201, 202, 211, 217, 218, 221

Y

Young's modulus, in magnetostriction, 222
  in quartz, 65
  in Rochelle salt, 79

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